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# EFFECTS OF MANUAL AND MECHANICAL *AMMOPHILA ARENARIA* REMOVAL TECHNIQUES ON COASTAL DUNE PLANT COMMUNITIES AND DUNE MORPHOLOGY

By

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## ABSTRACT


EFFECTS OF MANUAL AND MECHANICAL *AMMOPHILA ARENARIA* REMOVAL TECHNIQUES ON COASTAL DUNE PLANT COMMUNITIES AND DUNE MORPHOLOGY

Monique Rose Silva Crossman

The removal of invasive species as part of the restoration process can allow natives organisms to rebound. An ecosystem that incurs damages from invasive species is coastal sand dunes, which are dynamic systems. Some coastal sand dunes on the west coast of the United States have been invaded by *Ammophila arenaria*. The invasive grass, *A. arenaria,* is thought to alter and stabilize foredune morphology and reduce populations of native species. The objectives of my research are to examine the effects that manual and mechanical *A. arenaria* removal techniques have on coastal sand dune morphology and vegetative cover over time. The California State Parks Redwood District manages three coastal sand dune ecosystems where *A. arenaria* removal efforts have been conducted: Little River State Beach, Gold Bluffs Beach in Prairie Creek Redwoods State Park, and Tolowa Dunes State Park. I surveyed the vegetative cover at each of the three locations in each treatment method, manual and mechanical, and in untreated control plots during the summer and early fall of 2017. In order to measure dune morphology at restored and unrestored sites, I used an Unmanned Aerial Vehicle (UAV) that was flown over the mechanical removal and control areas. I then created a

Digital Elevation Model (DEM) from photos taken during the UAV flights using Structure from Motion software. Overall, both mechanical and manual treatments lowered *A. arenaria* cover. Mechanical removal lowered the foredune elevation compared to control areas and changed the dune morphology in treatment areas into hummocks at Little River. Although mechanical removal was effective at lowering *A. arenaria* cover, it also lowered native plant diversity compared to manual removal, but was higher than control diversity. With endemic species of concern on coastal sand dunes, manual removal of *A. arenaria* will afford greater native plant diversity and cover compared to mechanical removal.

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# INTRODUCTION

The invasion of non-native species causes large scale habitat alteration, and ecological restoration is one tool to reduce their impact. Invasive species are credited as one of the largest threats to endangered species and loss of biodiversity, second only to habitat loss (Wilcove et al. 1998). There are 50,000 non-native species in the United States, and $137 billion are spent annually in the U.S. in response to the damages incurred by non-native invasive species (Pimentel et al. 2000). The removal of invasive species as part of the restoration process can allow native organisms to rebound and return ecosystems to a less altered state (Hobbs and Harris 2001, Zavaleta et al. 2001). However, in order to restore an ecosystem’s structure and function, control of invasive species should include the management of ecosystem function and non-target species recovery (SER 2004, Zarnetske et al. 2010).

Coastal sand dunes are dynamic systems subject to a variety of natural and anthropogenic stresses, including impacts from invasive species. Coastal sand dunes make up 42% of the coastline of the Pacific Northwest region of the United States or about 1,000 km of shoreline (Wiedemann 1984, Wiedemann and Pickart 1996). Coastal sand dunes are an ever-changing environment, subject to high variability in wind speed, temperature, salinity, and spatial arrangement (Wiedemann 1984). The Pacific Northwest coastal sand dunes are subject to wet, rainy winters and warm, dry summers in addition to other extreme weather (Wiedemann 1984). High winds shift the sand and create a natural foredune, the ridge adjacent to the shore (Pickart and Sawyer 1998, McDonald 2015).

The ever-shifting mounds of the foredunes protect the terrestrial environment from storm surges and tsunamis by absorbing ocean influxes and acting as natural buffers (Mascarenhas and Jayakumar 2008). Coastal sand dune ecosystems have also experienced impacts of urban development, sea level rise due to global climate change, industrial and maritime development, mining, tourism and recreation (e.g., Lithgow et al. 2013). Lastly, a large human-induced impact to coastal dunes is the introduction and spread of invasive species, such as European beachgrass (*Ammophila arenaria* (L.) Link) (Wiedemann & Pickart 1996).

*Ammophila arenaria* is a hardy perennial grass native to Europe, but is invasive in coastal sand dunes along the coast of Australia, New Zealand, and Western North America. In its native range, *A. arenaria* is found on coastal sand dunes of the European coastline south of latitude 63 degrees N, such as the beaches of Great Britain (Huiskes 1979). *Ammophila arenaria* has adapted to the ever-changing and harsh dune habitat conditions, and is a rhizomatous grass that can reach a height of 120 centimeters (Huiskes 1979). *Ammophila arenaria* can withstand being buried by up to a meter of sand per year, and is strongly drought- and high-temperature tolerant (Huiskes 1979). Due to the tolerances of *A. arenaria*, this ‘ecosystem engineer’ has dominated many of the foredune environments of the Pacific Northwest (Wiedemann and Pickart 1996).

*Ammophila arenaria* was originally introduced over 100 years ago to a small area in Humboldt County (California) and has since expanded along the entire north coast of California. In 1901, roughly a 1-hectare area of *A. arenaria* was planted on Humboldt Bay’s North Spit, in hopes of stabilizing the inland dunes near a timber mill in Samoa, California (Buell et al. 1995). Other plantings of *A. arenaria* occurred near buildings and railroads in the Humboldt Bay Area to stabilize the sand in the early 1900's (Buell et al. 1995, Pickart and Sawyer 1998). Control and removal of *A. arenaria* in the Humboldt Bay Area began in the 1980's (Buell et al. 1995). In a study of aerial photographs, Buell et al. (1995) found a 574% increase in *A. arenaria* cover from 1939/1942 to 1989 on the North Spit dunes of Humboldt Bay. In comparison, aerial photographs of the Oregon coast from the 1930s shows little to no vegetation on the foredunes, an indication that *A. arenaria* had not invaded at that time (Wiedemann and Pickart 1996).

*Ammophila arenaria* alters dune morphology by stabilizing the foredunes and hampering dune migration. Wind, sand, water and vegetative cover are the most common influences to dune morphology (Wiedemann 1984). Prior to the *A. arenaria* invasion, the native foredune vegetative composition was dominated by *Elymus mollis* (American dune grass) and the morphology consisted of lower elevation dune hummocks (i.e., mounds) spaced close together (Wiedemann 1984). Researchers speculate that *A. arenaria* has increased the height of the foredunes up to an elevation of 10 meters above sea level (asl), which may be unnatural for the Pacific Northwest dunes system (Wiedemann and Pickart 1996). The stabilization of a foredune ridge can prevent sand from building up on the back dunes, which can "starve" the back dunes of windblown sand, altering the habitat and killing off native dune plant species (Wiedemann and Pickart 1996, Hart et al. 2012).

In addition to foredune stabilization, *A. arenaria* can cause declines in native populations of flora and fauna. The Western Snowy Plover (*Charadrius nivosus nivosus*) is listed as a threatened species by the U.S. federal government, and as a species of concern by the State of California (California State Park North Coast Redwoods District 2015). Snowy Plovers nest and breed on coastal sand dunes, and are the focus of restoration efforts in Pacific Northwest coastal sand dunes (Zarnetske et al. 2010, Hardy and Colwell 2012). Snowy Plovers prefer nesting sites where *A. arenaria* has been removed, either by mechanical, manual, chemical, burning or a combination of removal treatments has occurred (Muir and Colwell 2010, Zarnetske et al. 2010). Native dune mat is a community of annual and perennial flora that inhabit the foredunes and nearshore dune ridges (Pickart and Barbour 2007). *Ammophila arenaria* prevents the mobilization of sand to the back dunes, thus impacting native dune mat species (Wiedemann and Pickart 1996) such as the rare and endangered pink sand verbena (*Abronia umbellate* var. *breviflora*), beach pea (*Lathyrus japonicas*), Menzies' wallflower (*Erysimum menziesii*), and beach layia (*Layia carnosa*) (Mills 2015).

Many *A. arenaria* removal treatments have been employed along the western coast of the United States including using fire, mowing, pesticides, and mechanical and manual removal (Pickart and Sawyer 1998, Forys et al. 2009). Each treatment method provides some decline in *A. arenaria* vegetation cover. However, the two treatments most commonly used on the dunes of the California State Parks North Coast Redwood District beaches are manual and mechanical removal (Pickart and Sawyer 1998, Forys et al. 2009, Transou 2012, Wisehart 2012). Mechanical removal involves using bulldozers to bury *A. arenaria* up to 2 meters under the sand and regrade the foredune (Forys et al. 2009). In contrast, hand removal utilizes shovels to excavate the plant up to a depth of 0.6 meters

(2 feet); then the pulled *A. arenaria* vegetation is piled and burned to prevent the spread of its seeds (Forys et al. 2009). Manual removal is estimated to cost between $36,600 to $54,590/hectare depending on depth of burial and distance to site (Pickart 1997, Pickart and Sawyer 1998, Peterson 2004). In contrast, cost estimates for the mechanical treatment of *A. arenaria* range from $13,256 to $38,769/hectare, which may include equipment rental, operator salary, and fuel (Peterson 2004, Hyland and Holloran 2005). However, the lower mechanical removal cost estimate does not take into account retreatments after the initial burial, which may underestimate the total cost of removal. Mechanical removal, although it does not discern between native and invasive plants, may bury the rhizomes of *A. arenaria* far enough to allow natives a slight edge in recolonizing the dunes at first (Pickart and Sawyer 1998). This one-time advantage for native plants may allow them to outcompete *A. arenaria* for space.

Currently there are conflicting studies that have been conducted on the removal of *A. arenaria* and its effect on native plant communities. The California State Parks found that native species recover after *A. arenaria* removal in both mechanical and manual restoration sites (Forys 2015). However, a study by Zarnetske et al. (2010), of Washington and Oregon coastal sand dunes, found that native and endemic plant abundance declined in association with both mechanical and manual restoration techniques. Zarnetske et al. (2010) cited the high disturbance level of mechanical removal for hindering native plant re-establishment. In addition, Mills (2015) found that one year after treatment at Golds Bluffs Beach in northern California, there was no difference in native plant cover between mechanical and manual restored sites, and control plots had a higher abundance of native plants. Without clear information on the effectiveness of restoration treatments it can be difficult to make appropriate land management decisions.

Furthermore, removal of *A. arenaria*, can influence the morphology of the dunes, but more measurements to determine the extent of change are needed. Part of the goal of removing *A. arenaria* is to return the dunes to pre-invasion height and the ecosystem to its proper functioning state of flux (Zarnetske et al. 2010). Vaughan (2015) and McDonald (2015) found no difference between invaded sites and restored sites' elevation on northern California beaches. In contrast, Zarnetske et al. (2010) found that in the Pacific Northwest, the repetitive and intensive use of bulldozers to remove *A. arenaria* may have flattened the foredune, which was exhibited by the wider and shorter foredune than those observed in control (invaded unrestored) areas. The conflicting reports could be due to the equipment used to measure the dune morphology. Currently, the California State Parks use a Real Time Kinematic (RTK) global positioning system (GPS), which is accurate to within a centimeter for elevation. (Vaughan 2015). However, it is not a continuous data set as only one elevation point can be taken at a time (Vaughan 2015). Other techniques include 30-meter digital elevation models (DEM), and Light Detection and Ranging (LiDAR) data, which may not be at an appropriate scale or time interval to measure any difference among treatments and control sites (Vaughan 2015, McDonald 2015). Unmanned Aerial Vehicles (UAV), used with Structure from Motion (SfM), can produce a cloud of data points (location with elevation data) that can measure the dune topography with quality, and vertical accuracy comparable with RTK and LiDAR surveys (Mancini et al. 2013).

## Research Objectives

The objectives of my graduate thesis research were to examine the effects that manual and mechanical removal techniques of *A. arenaria* have on coastal sand dune morphology and vegetative cover and species abundance over time. The quantification of native dune vegetation cover at sites where removal of *A. arenaria* has occurred can assess the recovery of the plant community over time. By examining different treatment types of *A. arenaria* removal at different times since treatment, I observed time-dependent effects of removal on the non-target parameters, native dune plants and dune elevation changes in comparison to unrestored sites. Overall, my objectives were: 1) to determine if one removal treatment (manual or mechanical) is more effective at lowering the *A. arenaria* population and increasing the native dune plant population over the long term; and 2) to compare the dune morphology and elevation of treated and untreated sites to assess which treatment lowered the foredune and restored the morphology to pre-invasion conditions.

The results of my research have the potential to help land managers select the most effective removal techniques for *A. arenaria* in the future. The long-term effects of *A. arenaria* removal could have a profound effect on dune vegetation diversity, morphology and the dunes' ability to mitigate storm surges and coastal changes. My Masters research has allowed for a refinement in removal and monitoring methods that can improve habitats for threatened species such as Snowy Plover and endangered dune mat flowers such as beach layia, and Menzies' wallflower.

# MATERIALS AND METHODS

## Study Sites

The California State Parks Redwood District manages three coastal sand dune ecosystems in which they have conducted *A. arenaria* removal efforts: (1) Gold Bluffs Beach in Prairie Creek Redwoods State Park; (2) Little River State Beach; and (3) Tolowa Dunes State Park (Table 1 and Figure 1). In 2009, mechanical removal of *A. arenaria* began at Little River State Beach. Mechanical removal utilized bulldozers to bury *A. arenaria* up to 2 meters under the sand and regrade the foredune to a 2% to 5% slope (Forys et al. 2009, Forys 2015). After the initial treatment at Little River State Beach, manual removal was performed approximately three times for the first year and one to two times per year after the first year, to treat resprouts of *A. arenaria*. Hired crews used shovels to excavate the plant up to a depth of 0.6 meters during manual retreatment (Forys et al. 2009, Mills 2015). Seeding of beach morning glory (*Calystegia soldanella*), beach bursage (*Ambrosia chamissonis*), yellow sand verbena (*Abronia latifolia*), beach pea (*Lathyrus littoralis*), beach buckwheat (*Eriogonum latifolium*), yarrow (*Achillea millefolium*), dune goldenrod (*Solidago spathulata*), seaside daisy (*Erigeron glaucus*), and glehnia (*Glehnia llittoralis* subsp.*leiocarpa*) occurred at Little River after initial mechanical removal of *A. arenaria* (Forys 2015). Gold Bluffs Beach underwent the same mechanical treatment as Little River State Beach using bulldozers in 2013, with some areas receiving only manual removal (Transou 2012). Some seeding of yellow sand verbena (*Abronia latifolia*), pink sand verbena (*Abronia umbellata* var. *breviflora*), and American glehnia (*Glehnia littoralis* subsp. *leiocarpa*.) took place after intimal mechanical treatment at Gold Bluff Beach (Transou 2012). In addition, beach strawberry (*Fragaria chiloensis*) and beach evening primrose (*Camissoniopsis cheiranthifolia*) were transplanted into the treatment area at Gold Bluffs Beach (Transou 2012). Tolowa Dunes, due to its cultural significance, has undergone only manual removal of *A. arenaria* since 2010 (Wisehart 2012).

Table 1. The start date of initial treatment to remove *Ammophila arenaria*, treatment method, and acreage treated at each of my research sites: Little River State Beach, Tolowa Dunes State Park, and Gold Bluffs Beach in Prairie Creek Redwoods State Park. Follow-up manual treatment occurred approximately 3 times the first year, and once to twice a year the following years for all treatment types (Forys et al. 2009, Transou 2012, Wisehart 2012, and Mills 2015).

| **Site** | **Start of Restoration** | **Treatment Method** | **Acres Treated** |
|---|---|---|---|
| **Little River** | 2009 | Mechanical (seeding occurred) | 42 |
| **Tolowa Dunes** | 2010 | Manual | 27 |
| **Gold Bluffs** | 2013 | Mechanical and manual (seeding occurred) | 73 (mechanical) and 11(manual) |

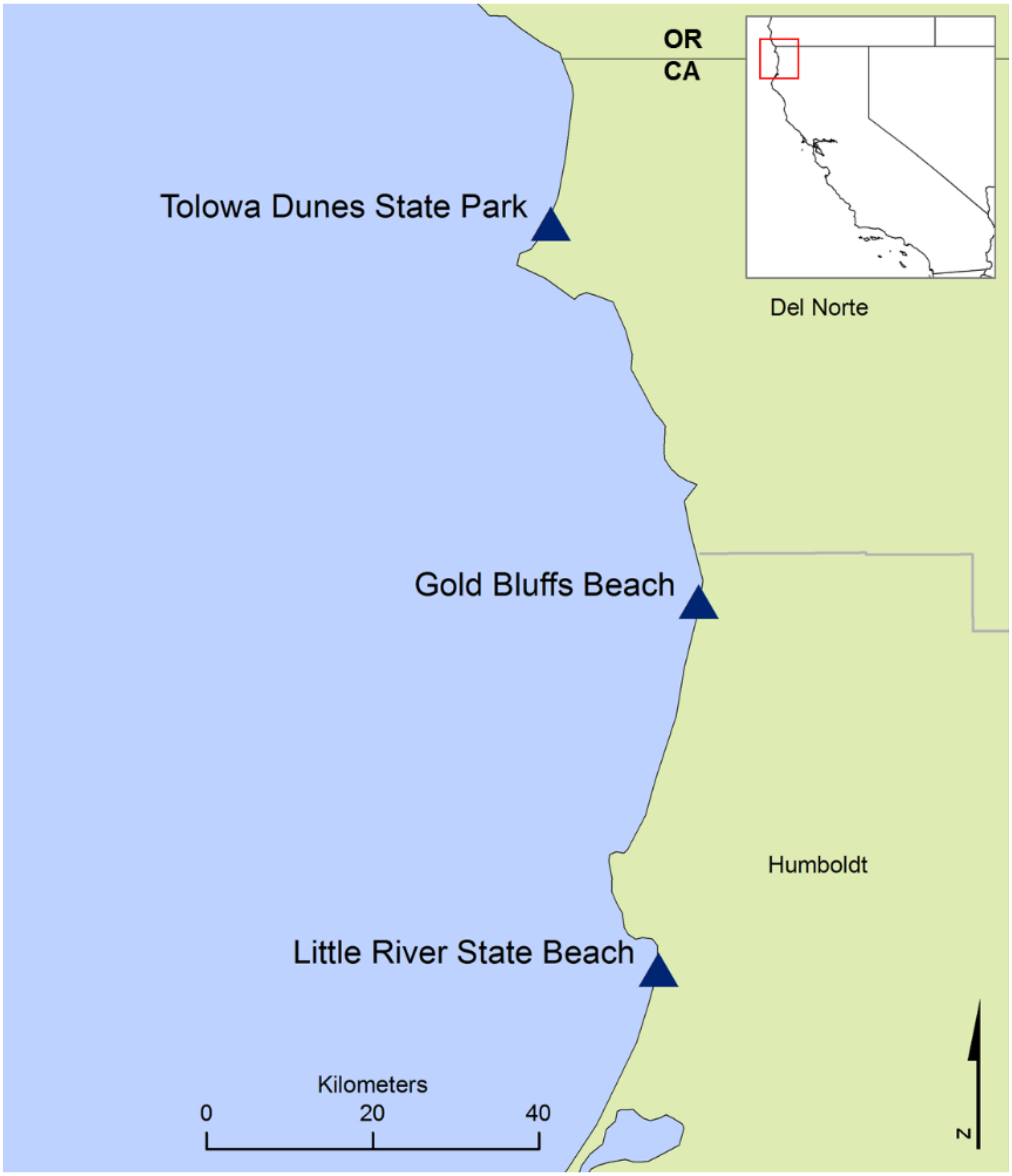


Figure 1. Study site locations in three California State Parks: Tolowa Dunes State Park, Gold Bluffs Beach in Prairie Creek State Park and Little River State Beach, within Humboldt and Del Norte counties in northern California (Esri 2009, TIGER 2016).

## Vegetation Monitoring

In order to measure the cover of foredune vegetation in areas of mechanical and manual *A. arenaria* removal, I re-surveyed vegetation in established plots of manual and mechanical removal and adjacent unrestored sites at Gold Bluffs Beach and Little River State Beach (Mills 2015, Forys et al. 2009), as well as in new vegetation monitoring plots at Tolowa Dunes (Figure 2). I conducted vegetation surveys once in May and again in September 2017 at all three sites. I located pre-established plots using a Garmin GPSmap 60CSx unit, with an accuracy of less than 10 m. I measured a total of 37 previously surveyed 5m × 5m ($25m^2$) plots (i.e., 28 within Gold Bluffs Beach, and nine within Little River State Beach; there were no pre-established plots at Tolowa Dunes). I did not re-survey two pre-established plots at Gold Bluffs Beach, one in a manual removal area and the other in a mechanical removal area, due to erosion of the foredune leaving the plots in the waveslope, the area below the high tide line, where vegetation does not typically grow. Mills (2015) measured vegetation cover at Gold Bluffs Beach in 2012, before removal of *A. arenaria* and again one year after treatment. Forys et al. (2009) monitored vegetation at Little River State Beach before removal in 2009, as well as once every year after the initial mechanical treatment until 2016. I also used ArcMap (version 10.4.1) to randomly select twelve new 25 $m^2$ plots at Tolowa Dunes, six within manual removal areas and six within unrestored control areas.

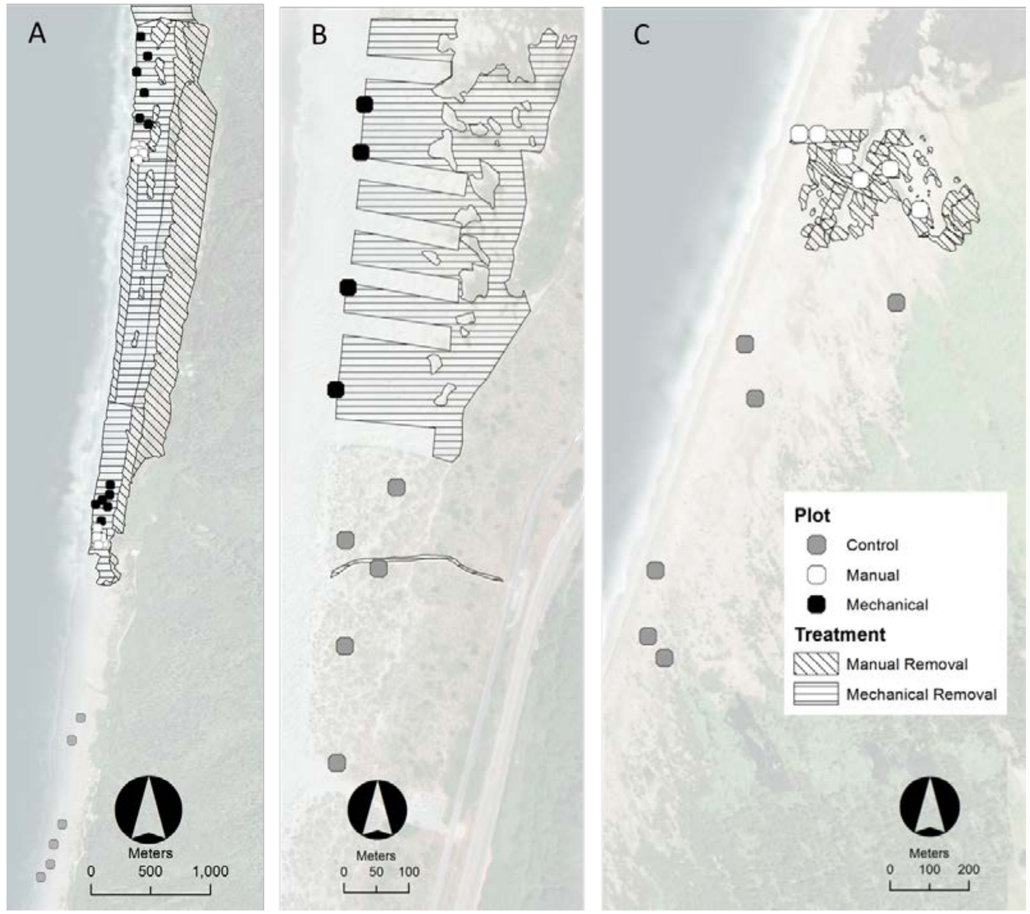


Figure 2. Location of vegetation monitoring plots and treatment area at: (A) Gold Bluffs Beach, (B) Little River State Park, and (C) Tolowa Dunes State Park along the north coast of California (see Figure 1). Gray circles are control vegetation monitoring plots in which *Ammophila arenaria* was not treated. White circles are vegetation monitoring plots where manual removal of *Ammophila arenaria* occurred. Black circles are vegetation monitoring plots where mechanical removal of *Ammophila arenaria* occurred. Total treatment area is covered in either diagonal lines for manual removal, or horizontal lines for mechanical removal (Mills 2015, Esri 2009).

Within the *A. arenaria* survey plots, I measured the vegetation cover in fifteen 1 $m^2$ quadrats. In a previous study (Mills 2015), each plot was marked with rebar at the northwest corner. In the event that I was unable to find a rebar marker for a plot, I used a Garmin GPS to reestablish the plot and marked the plot with new rebar. Along the eastern edge of each 25 $m^2$ plot, I placed three equally-spaced transects perpendicular to the shoreline at intervals of 6.25 m, 12.50 m, and 18.75 m. I placed 1 $m^2$ quadrats to measure plant vegetation cover along each transect at 4.6 m, 9.1 m, 13.7 m, 18.3 m and 22.9 m (Figure 3). In each 1 $m^2$ quadrat, I measured the percentage cover for each species of dune vegetation and non-vegetation cover (cobble, crust, litter, sand and wood) then transformed the percentages into a modified Braun-Blanquet et al. (1932) cover scale to match previous data collected (Table 2). Cobble was defined by the Wentworth scale as sediment with a grain diameter between 65 to 250 mm (Wentworth 1922). Crust was biogenic soil crust, which is made up of cyanobacteria, lichen, mosses and other organisms (Belnap and Lange 2001). Litter was considered any organic cover not rooted, that was not woody and usually dead (Michelle Forys, personal comm. 2017). Wood cover was defined as any cover material not rooted and made of woody material, such as logs and twigs (Michelle Forys, personal comm. 2017). Sand was defined as any sediment with a grain diameter between 1-0.125 mm (Wentworth 1922).

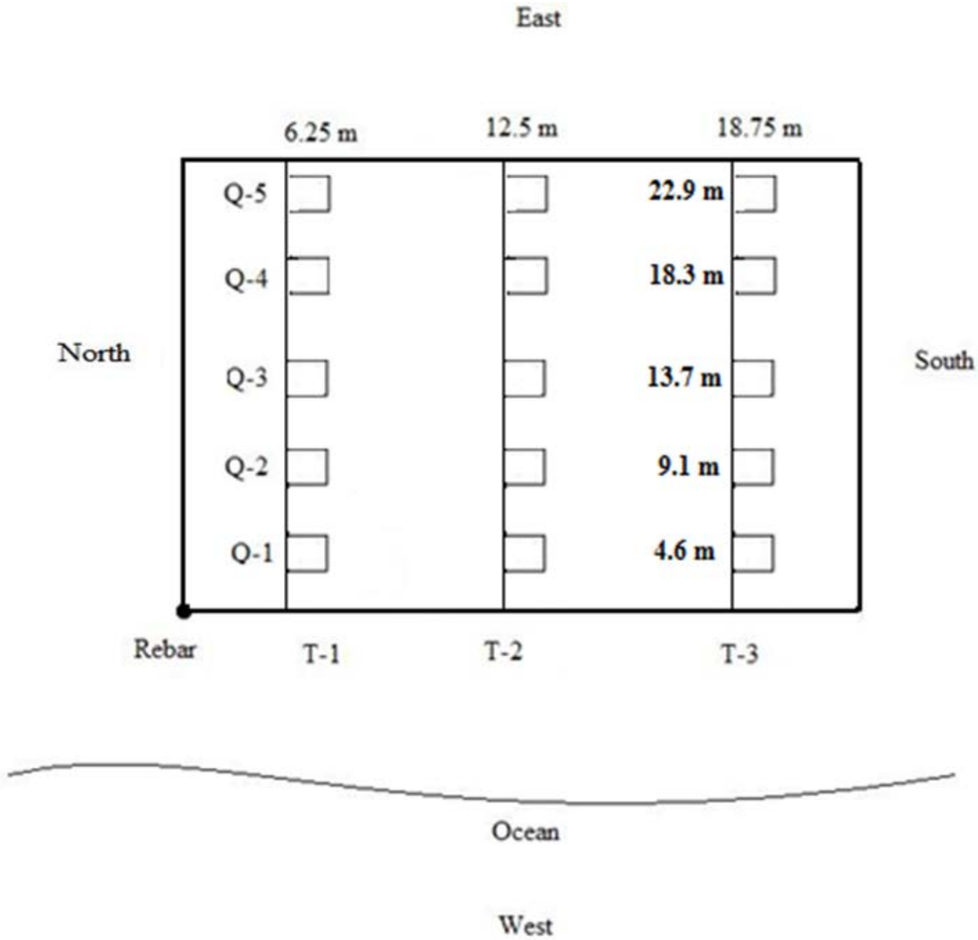


Figure 3. Plot layout for plant vegetation cover measurements. I established 25 $m^2$ plots with three transects at 6.25 m, 12.5 m and 18.7 5m on the eastern edge of the 25 $m^2$ plot. Along each transect, I placed a 1 $m^2$ plant vegetation cover plot at 4.6 m, 9.1 m, 13.7 m, 18.3 m and 22.9 m away from the western boundary of the 25 $m^2$ plot (methods adapted from Mills 2015).

Table 2. Modified Braun-Blanquet cover classes used for vegetation and cover measurements in $1m^2$ quadrats (Braun-Blanquet et al. 1932, Mills 2015).

| **Cover Class** | **Range of Cover (%)** |
|---|---|
| **0** | 0 |
| **1** | >0 to <1 |
| **2** | 1 - <5 |
| **3** | 5 - <10 |
| **4** | 10 - <25 |
| **5** | 25 - <50 |
| **6** | 50 - <75 |
| **7** | 75 - <100 |

Statistical analysis included a comparison of *A. arenaria* percentage cover, and diversity for each treatment type at each site. I analyzed the modified Braun-Blanquet cover scale of *A. arenaria* at each treatment and site by using a Kruskal-Wallis test ($\alpha$=0.05) and a Dunn's Test of Multiple Comparisons Using Rank Sums to assess differences among groups, with a Benjamini-Hochberg adjustment to p-values in R package dunn.test (2017) (Dunn 1964). I calculated Shannon's diversity index for each site and treatment type before and after treatment. I used a Kruskal-Wallis test to assess differences between treatment type's Shannon's diversity indexes. A post-hoc Dunn's test was done to the Shannon diversity differences to groups with a Kruskal-Wallis test ($\alpha$=0.05).

I performed a non-metric multidimensional scaling (NMDS) ordination using the Jaccard index of dissimilarity of the vegetation cover, in percentage cover, at the three sites for the three categories of treatment: mechanical, manual and untreated controls. NMDS was used to avoid assumptions of a linear relationship among variables and because it uses ranked distances from the distance matrix (McCune and Grace 2002). I deleted rare taxa that occurred in less than 1% of the quadrats, a modified approach of deleting rare species from McCune and Grace (2002). The NMDS generates a set of orthogonal synthetic axes to plot the differences in species composition for each plot spatially (McCune and Grace 2002, Rogers et al. 2008). Using the R package vegan (2018), I ran the ordination for 1,000 maximum iterations and 1,000 real runs. McCune and Grace (2002) suggest using NMDS results with stress less than 0.2. I performed a permutational multivariate analysis of variance (PerMANOVA) on the Jaccard distances for the sites to assess differences in the group means of vegetation composition for the most recent vegetation cover measured (September 2017) (Anderson 2001, McCune and Grace 2002). In a perMANOVA, the sum of squared distances is calculated from the average interpoint distance of each group to assess difference between the treatment types composition of cover.

## Dune Morphology Survey

In order to measure dune morphology at restored and unrestored sites, I used a DJI Phantom 4 Unmanned Aerial Vehicle (UAV) with a 12.4M camera and ground control points with a Trimble Juno 5, with an accuracy between 1 to 4m. The UAV was flown by a licensed UAV operator over the three treatment types at an altitude of 75 m. Data collection occurred in September 2017 at Gold Bluffs Beach, and March 2018 at Little River State Park. The UAV operator set the camera mounted on the UAV gimbal to take one shot per second, for 70% overlap, with waypoints turned on to record GPS points for the photographs. I processed the photographs in SfM software, Agisoft PhotoScan 1.3.5, in order to create a redundant set of overlapping images with which to reconstruct the 3-dimensional geometry of the dunes. In order to line up the images, I first found the overlapping points of in the photographs using SfM. Next, I created a pixel-based stereoscope with the waypoint data and photographs to create a digital elevation model (DEM) of the dunes (Mancini et al. 2013). I used BlueSpray beta 24 to extract the highest elevations along the nearshore dunes in each treatment area. A Kruskal-Wallis test was used to assess any differences among the foredune heights in each treatment and control area.

# RESULTS

## Vegetation Analysis

The comparison of both mechanical and manual treatments lowered *A. arenaria* cover in restoration areas. A comparison of *A. arenaria* resprouts at Gold Bluffs Beach found that mechanical removal was slightly more effective at reducing cover of *A. arenaria* compared to manual removal at all time intervals compared (manual and mechanical: 1 year Z test= 8.55, p-value< 0.05; 4 years (May) Z-test= 2.65, p-value= 0.005; 4 years (September) Z-test= 2.19, p-value=0.0171) (Figure 4 and Appendix B). This advantage is greater directly after removal and levels out over time (manual and mechanical 1 year Z test= 8.55, p-value< 0.05). Tolowa Dunes had the lowest *A. arenaria* cover measured in manual removal plots, with a mean cover class and standard error of 1.02±0.15 (which is less than 1% cover of *A. arenaria*) for September 2017 monitoring (Figure 5 and Appendix C). Gold Bluffs Beach, Little River (Figure 6), and Tolowa Dunes had significantly different percentage cover of *A. arenaria* among their treated areas and the adjacent controls for all time steps (Gold Bluffs Beach: control and manual (Appendix B, Appendix C, Appendix D).

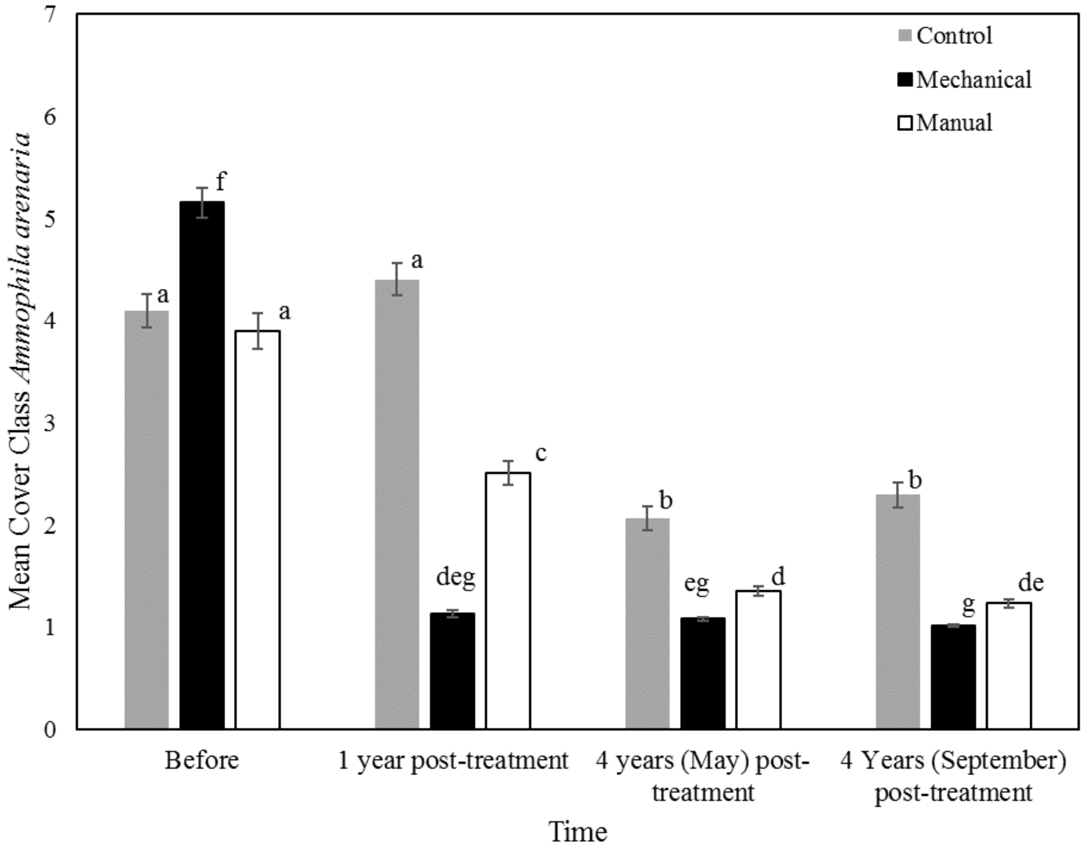


Figure 4. Mean cover class of *Ammophila arenaria* with one standard deviation error bars (in a modified Braun-Blanquet cover class (Table 2)) at Gold Bluffs Beach before removal (July 2012-January 2013), one year post-treatment (February 2014), and 4 years post-treatment (May and September 2017) in manual, mechanical and control plots. Letters correspond to Dunn's test groups with $\alpha<0.05$ (Appendix B).

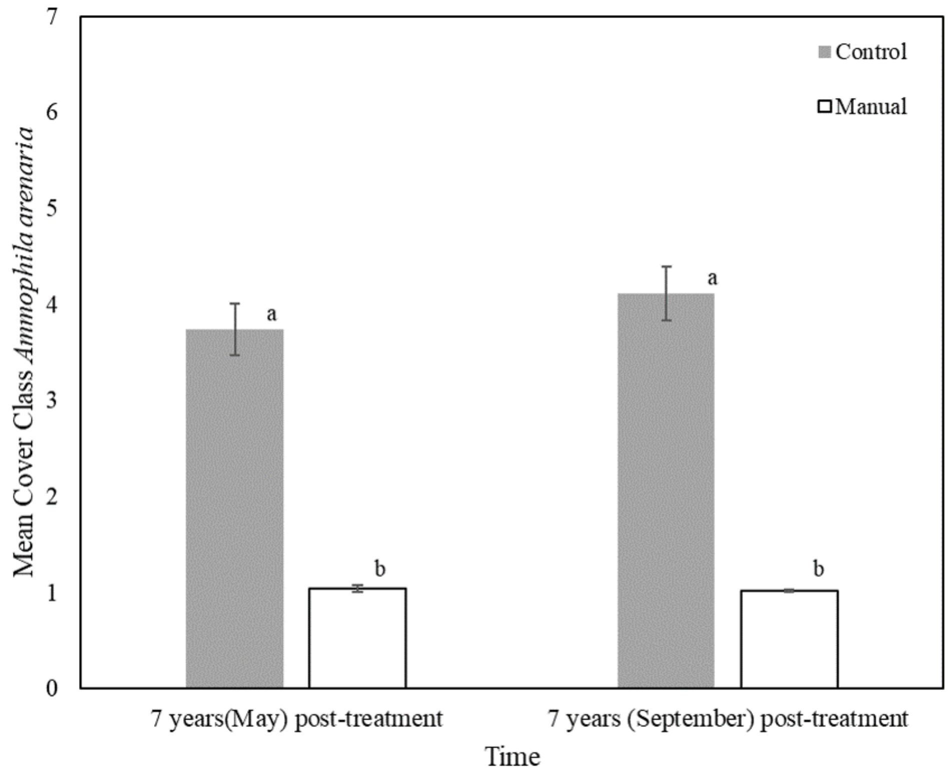


Figure 5. Mean cover class of *Ammophila arenaria* with standard error bars (in a modified Braun-Blanquet cover class (Table 2)) at Tolowa Dunes seven years post-treatment (May and September 2017) in mechanical and control plots. Letters correspond to Dunn’s test groups α< 0.05 (Appendix C).

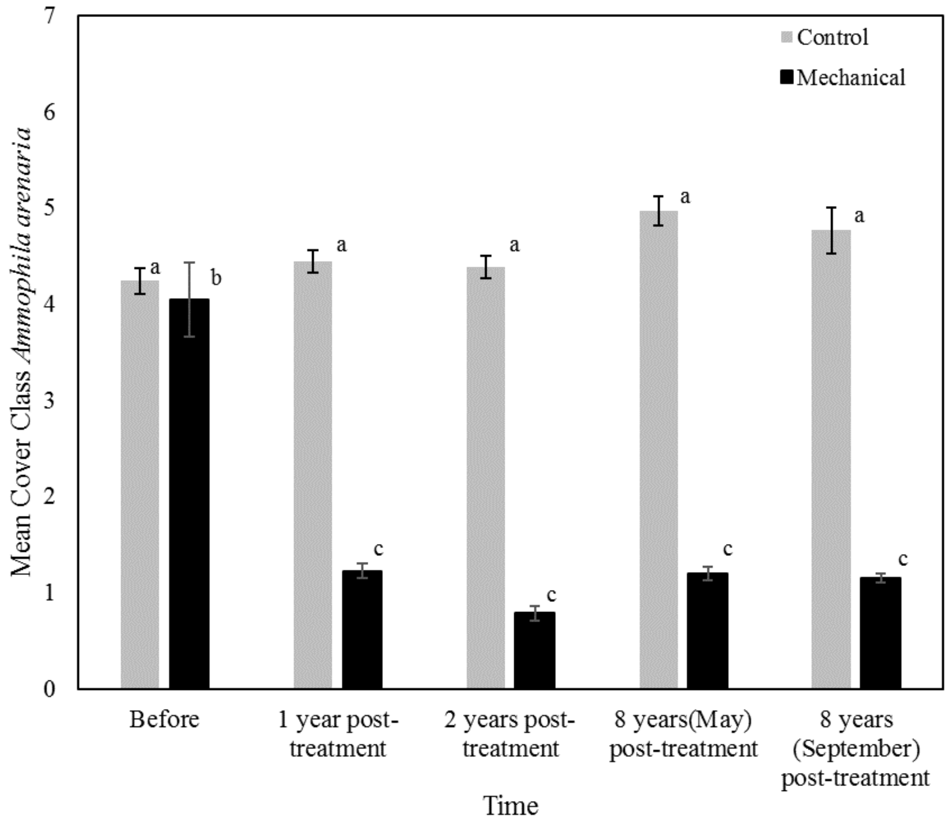


Figure 6. Mean cover class of *Ammophila arenaria* with standard error bars (in a modified Braun-Blanquet cover class (Table 2)) at Little River State Park before treatment (2009), and one year (2010), 2 years (2011) and 8 years (May and September 2017) post-treatment in manual and control plots. Letters correspond to Dunn’s test groups α<0.05 (Appendix D).

The average cover class of *A. arenaria* in control plots varied from site to site and over time. Gold Bluffs Beach exhibited a reduction of *A. arenaria* cover in the control sites over time without treatment (Figure 4). Control areas at Little River started with a similar mean cover class of *A. arenaria* (4, or 10 to 24% cover) as the mechanical treated areas mean cover class before treatment, and the control mean cover class stayed contestant over time (Figure 6). Tolowa Dunes mean *A. arenaria* cover class in either control or manual removal areas did not vary from their spring to fall 2017 measurements (Figure 5).

There were shifts in vegetation composition observed at Gold Bluffs Beach after treatment. Plant species diversity in the control plots at Gold Bluffs Beach stayed the same over the four year time period for both native and non-native species (Control before and after: native Z-test= -0.765, p-value= 0.256; non-native Z-test= -0.715, p-value= 0.254) (Figure 7 and Appendix E). Native species diversity stayed the same (Z-test= -0.459, p-value= 0.323) and non-native diversity declined in manual plots at Gold Bluffs (Z-test= -7.362, p-value= 0.00) (Appendix E). Whereas, in mechanical areas Shannon's Diversity index of both native and non-native species decreased 4 years after removal of *A. arenaria* at Gold Bluff Beach (native: Z-test= 3.450618, p-value=0.0008; non-native: Z-test= 8.536 $p$-value$<0.05$) (Appendix E).

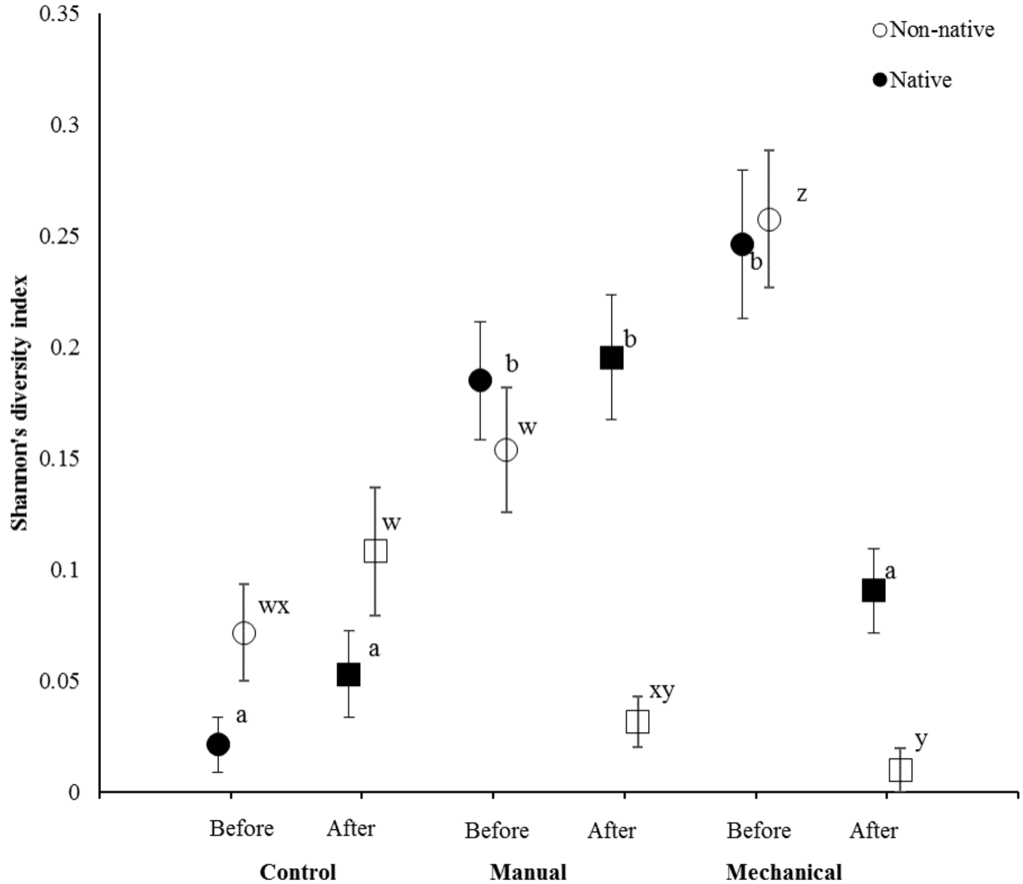


Figure 7. Shannon's diversity index for vegetation in all three plots types (control, manual and mechanical removal) at Gold Bluffs Beach before removal (July 2012-January 2013) in circles and 4 years after removal (September 2017) in squares. Native diversity is black and non-native is white. Letters correspond to Dunn's test groups at α<0.05 (Appendix E).

At Little River, diversity of non-native plants declined over the 8 years since treatment. Mechanical non-native diversity decreased after treatment (Z-test= 5.54, p-value<0.05 (Figure 8 and Appendix E). Within control areas, non-native diversity decreased, but not as low as mechanical (Z-test= 2.65, p-value= 0.008) (Figure 8 and Appendix E). Native diversity stayed constant over time in both control and mechanical treatment areas (Kruskal-Wallis chi-squared = 4.6752, df = 3, p-value = 0.197) (Figure 8).

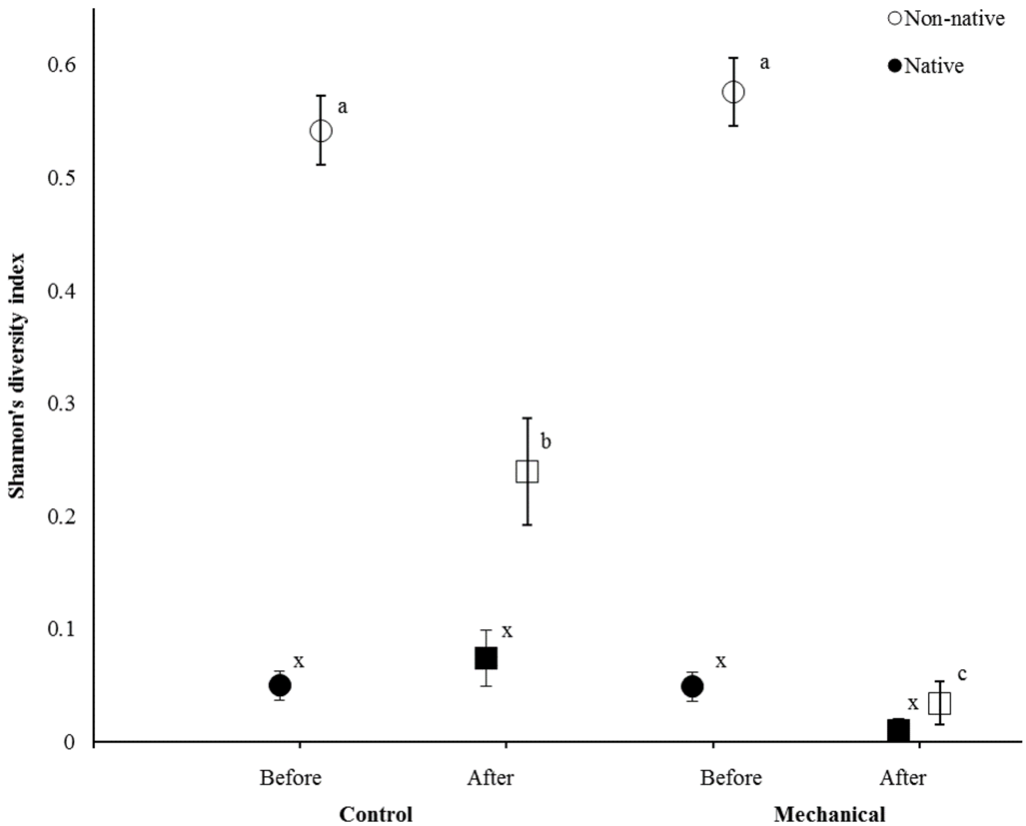


Figure 8. Shannon’s diversity index for vegetation in control and mechanical treatment plots at Little River before (2009) in circles and 8 years after removal (September 2017) in squares. Native diversity is black and non-native is white. Native diversity was not significantly different over time for all treatments (Kruskal-Wallis chi-squared = 4.6752, df = 3, p-value = 0.1972). Letters correspond to Dunn’s test groups at $\alpha<0.05$ (Appendix E).

At Tolowa Dunes, some differences in diversity between manual removal and control areas were observed. Non-native diversity was the same between control and manual treatment areas (Kruskal-Wallis chi-squared = 0.19377, df = 1, p-value = 0.6598) (Figure 9), whereas native diversity differed between manual and control areas, with higher native diversity in manual areas (Kruskal-Wallis chi-squared = 21.551, df = 1, p-value <0.05) (Figure 9).

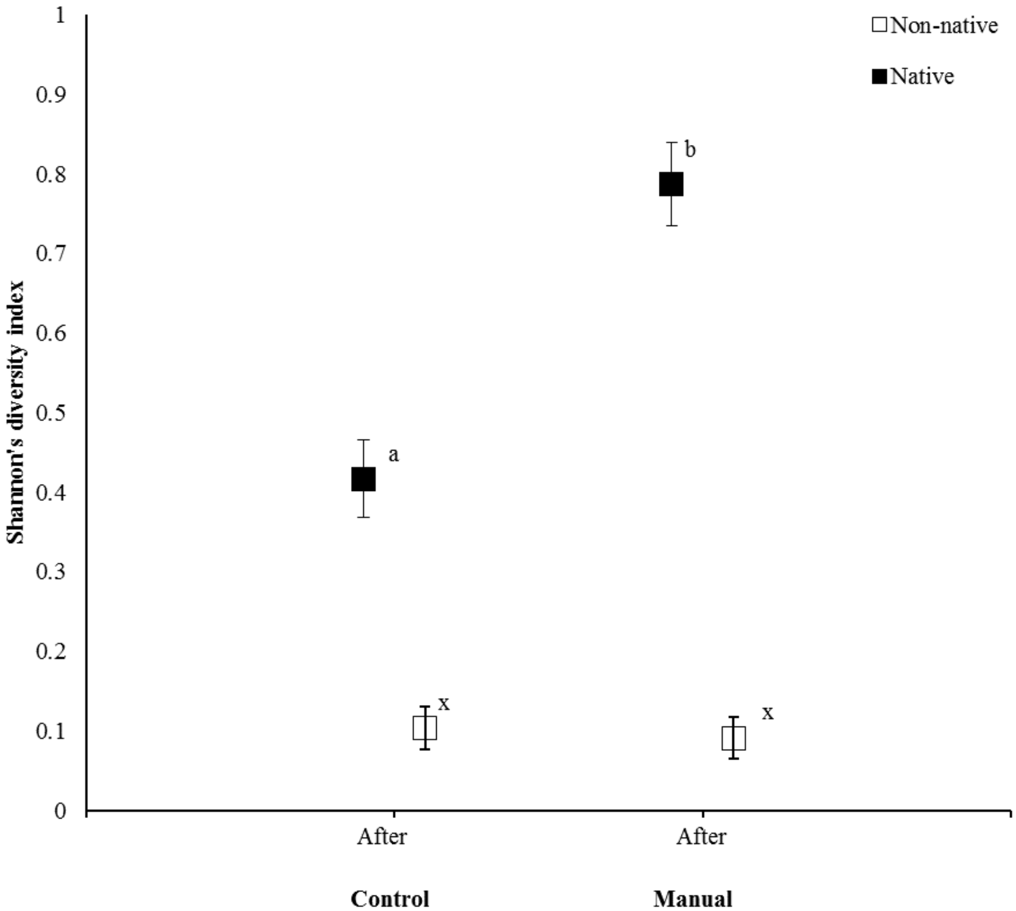


Figure 9. Shannon’s diversity index for vegetation in control and manual treatment plots at Tolowa Dunes 8 years after removal (September 2017). Native diversity is black and non-native is white. Native diversity was significantly different over time for all treatments (Kruskal-Wallis chi-squared = 21.551, df = 1, p-value <0.05). Non-native diversity did not differ between treatments (Kruskal-Wallis chi-squared = 0.19377, df = 1, p-value = 0.6598).

The NMDS ordination plots exhibited similarity in vegetation composition within each treatment type at each site. The ordination plot of vegetation cover data collected from Gold Bluffs Beach shows a tight grouping of mechanical plots (indicating compositional similarity among plots) and a looser grouping of manual and control plots with considerable overlap (indicating relative compositional dissimilarity among plots)

(Figure 10). Control plots were more associated with litter ($R^2$ =0.3382, p-value= 0.001), whereas manual and mechanical plots were associated with cobble ($R^2$ =0.0111, p-value= 0.092). A perMANOVA for the treatments at Gold Bluffs Beach found significant differences among treatments with a low $R^2$ (F=31.88, df= 2, $R^2$= 0.1326, p-value=0.005). Little River's NMDS ordination plot showed a tighter grouping of mechanically treated plots compared to control plots, which indicates that control plots at Little River had more variation in cover than mechanical plots (Figure 11). Litter was more associated with control plots ($R^2$ =0.1955, p-value= 0.001) and shell with mechanical plots ($R^2$ =0.0705, p-value= 0.014). A perMANOVA between Little River's mechanical and control Jaccard distances was significant with a higher $R^2$ (F= 104.56, df=1, $R^2$ = 0.440, p-value= 0.005). Tolowa Dune's NMDS ordination plot showed minimal overlap between control plots and manual plots, suggesting the vegetation cover differed among most of plots (Figure 12). Litter and crust where more associated with control plots (litter: $R^2$ = 0.0843, p-value= 0.002, crust: $R^2$ = 0.0305, p-value= 0.075) whereas cobble and shell where more associated with manual plots (cobble: $R^2$ = 0.0940, p-value= 0.001, shell: $R^2$ = 0.0649, p- value= 0.004). A perMANOVA between Tolowa Dunes manual and control Jaccard distances was significant with a low $R^2$ (F= 84.126, df=1, $R^2$ = 0.321, p-value= 0.005).

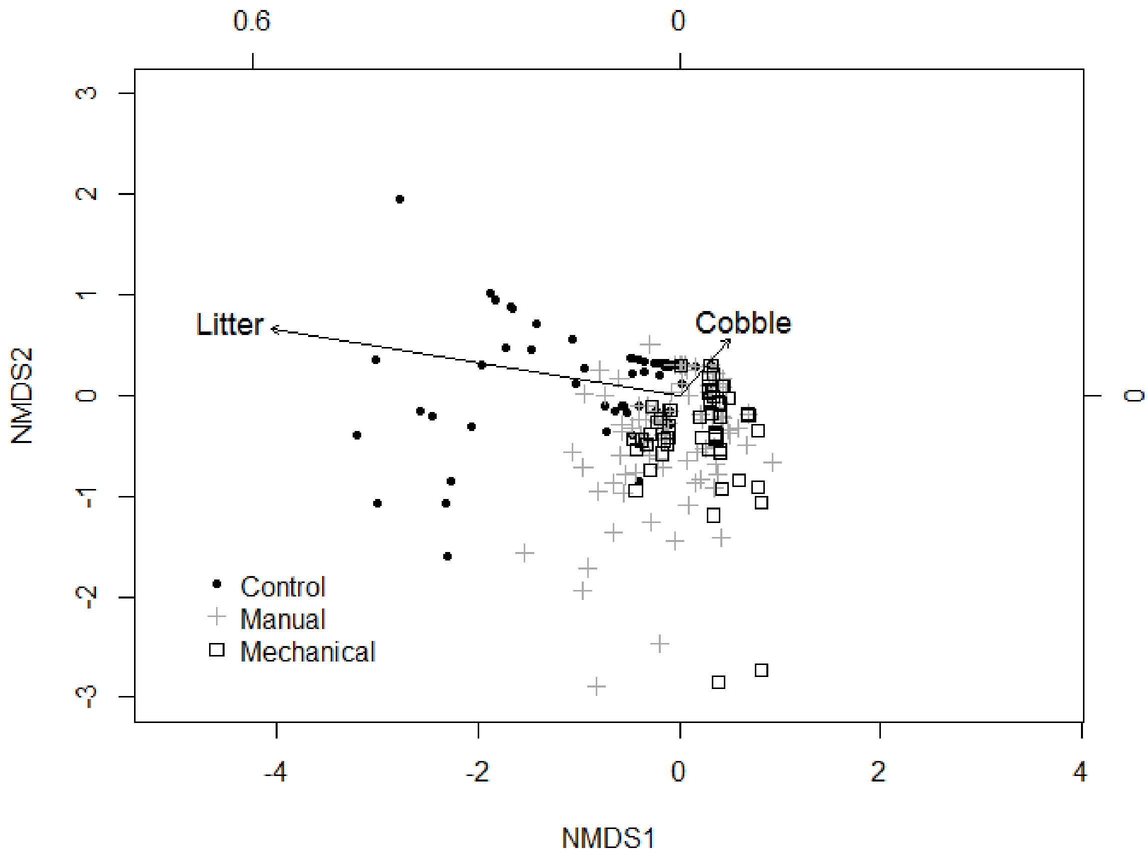


Figure 10. Gold Bluffs Beach NMDS ordination, with 2 dimensions, of treatment groups with control (black circles), manual (gray pluses), and mechanical (open black squares) vegetation cover plots (with sand cover included). The stress was 0.138. Vectors are non-vegetation cover recorded in plots: litter: $R^2$ =0.3382, p-value= 0.001, cobble: $R^2$ =0.0111, p-value= 0.092.

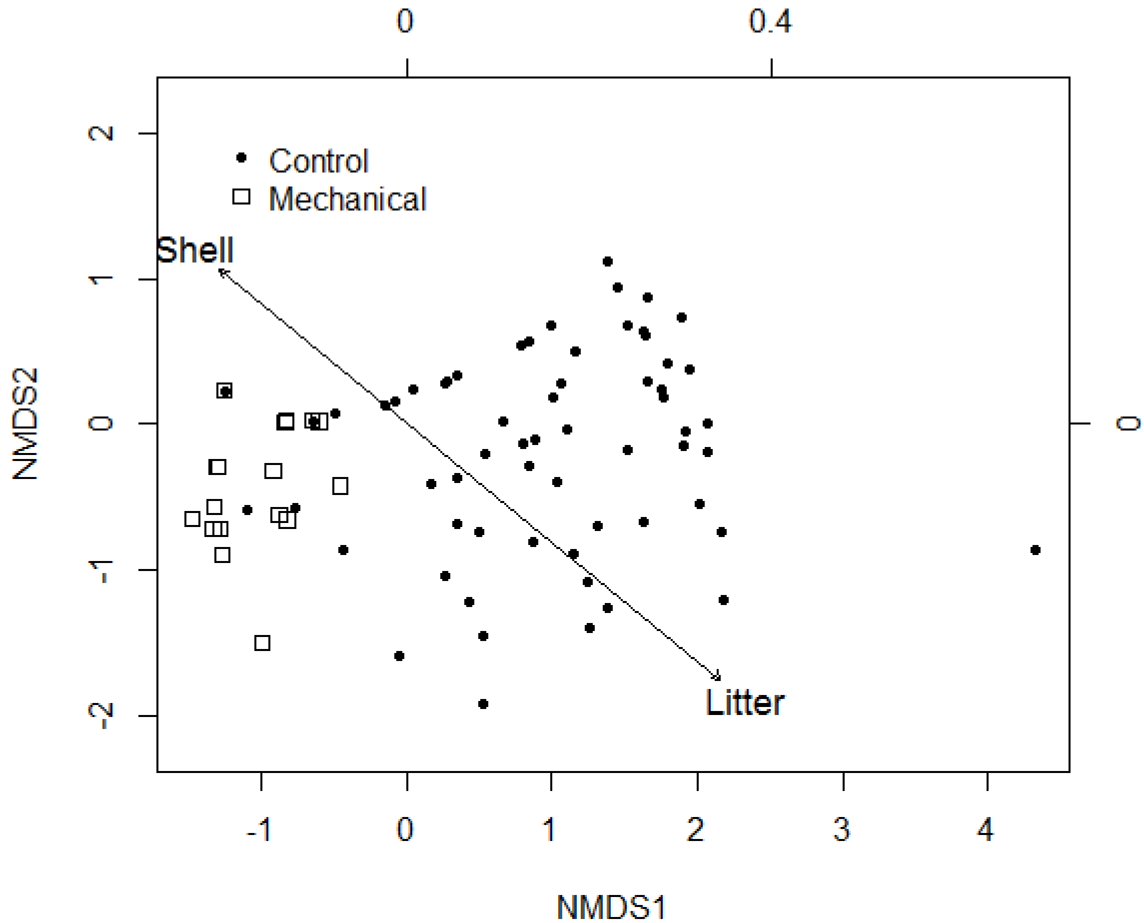


Figure 11. Little River NMDS ordination, with 2 dimensions, of treatment groups with control (black circles), and mechanical (open black squares) vegetation cover plots (with sand cover included). The stress was 0.115. Vectors are non-vegetation cover recorded in plots: litter: $R^2$ =0.1955, p-value= 0.001, shell: $R^2$ =0.0705, p-value= 0.014.

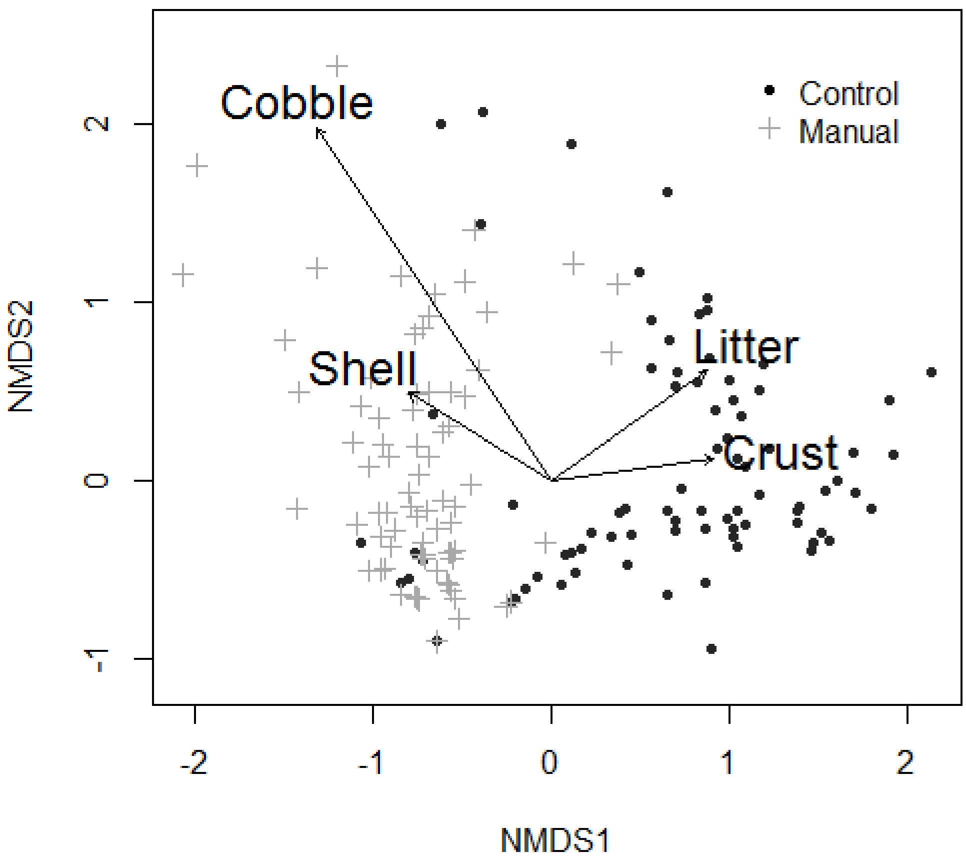


Figure 12. Tolowa Dunes NMDS ordination, with 2 dimensions, of treatment groups with control (black circles), and manual (gray pluses) vegetation cover plots (with sand cover included). The final stress was 0.139. Vectors are non-vegetation cover recorded in plots: cobble: $R^2$ = 0.0940, p-value= 0.001, shell: $R^2$ = 0.0649, p- value= 0.004, litter: $R^2$ = 0.0843, p-value= 0.002, crust: $R^2$ = 0.0305, p-value= 0.075.

## Dune morphology

Dune morphology captured with UAV imagery showed differences between foredune height and formation between control and mechanical treatment areas at the sites surveyed. At Gold Bluff's Beach the overall shape of the foredune in 2017 was raised linear mounds perpendicular to the shoreline (Figure 13). In control areas, the foredune was higher at one end and lower at the other but also had the same shape as the mechanically treated area. The foredune height was higher in control areas, with a mean and standard deviation of 10.49 ± 2.07 m, than mechanical treated areas with a mean and standard deviation of 8.32 ± 0.79m (Kruskal-Wallis chi-squared = 126810, df = 1, p-value<0.05) (Figure 14).


Figure 13. Elevation (m) in control and mechanical treatment areas at Gold Bluffs Beach in Prairie Creek State Park, CA in September 2017. Highest elevation in black and lower elevation white, with mechanical treated areas outlined in black polygons (Esri 2009.).

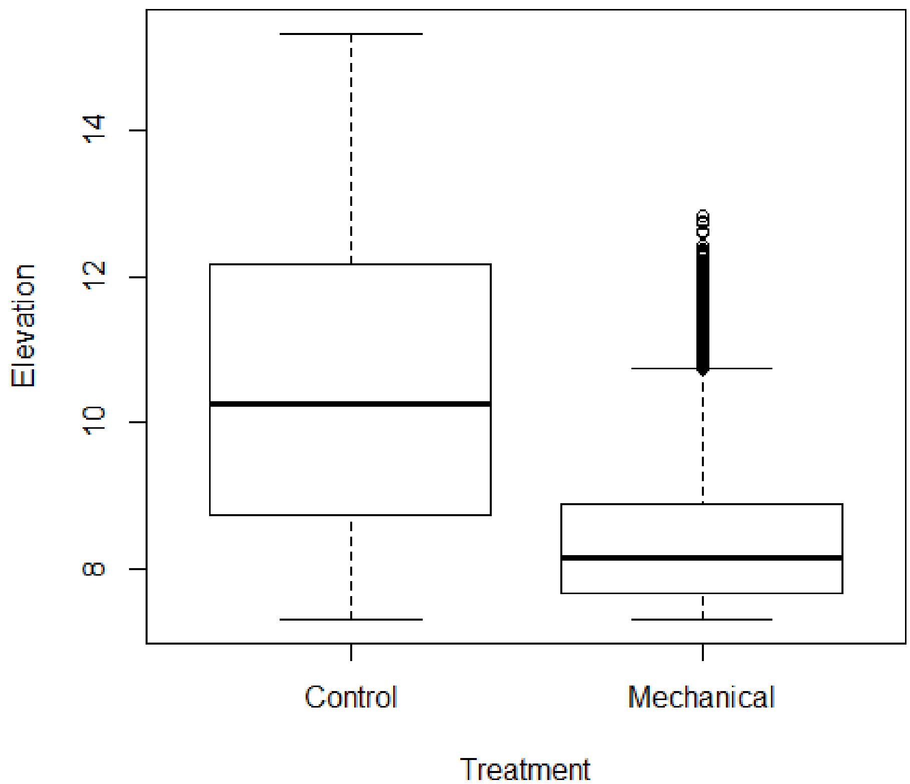


Figure 14. Foredune elevation (m) for control and mechanical treatment areas at Gold Bluffs Beach in September 2017. Dots are outliers.

At Little River, there was also a difference in dune morphology and foredune height between mechanical and control treatment areas. In the mechanical removal areas, the foredune was in the shape small dune hammocks, small "U" shaped mounds perpendicular to the ocean. In the control areas, the foredune was a tall ridge perpendicular to the ocean. The foredune height was significantly lower in the mechanical treated areas with a mean and standard deviation of 6.04 ± 0.23 m, than the control areas with a mean and standard deviation of 6.44 ± 0.32 m (Kruskal-Wallis chi-squared = 506.51, df = 1, p-value <0.005) (Figure 16). This difference in height was not as large as Gold Bluffs Beach, but mechanical treated areas were still lower than the control areas.

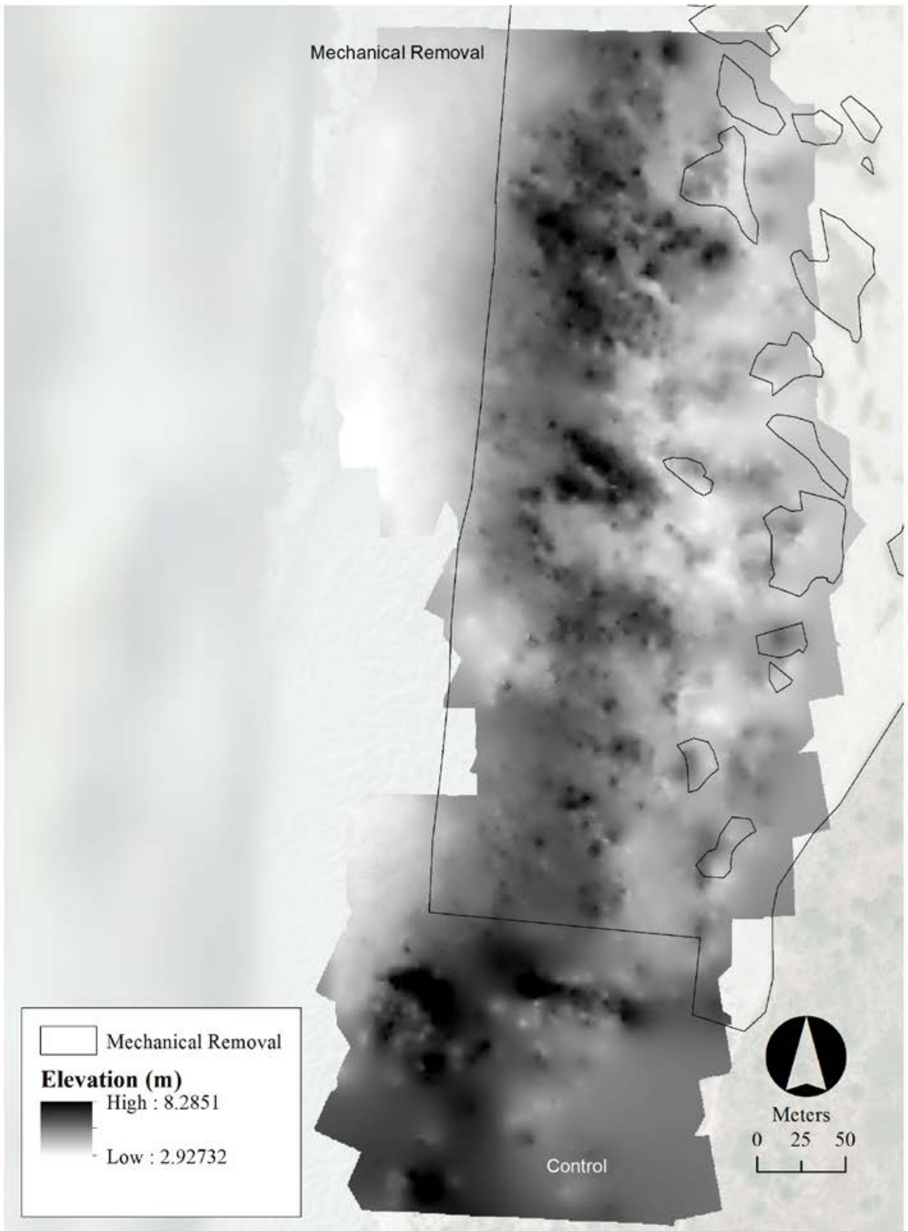


Figure 15. Elevation (m) in control and mechanical treatment areas at Little River State Park in March 2018. Highest elevation in black and lower elevation white, with mechanical treated areas outlined in black polygons (Esri 2009.).

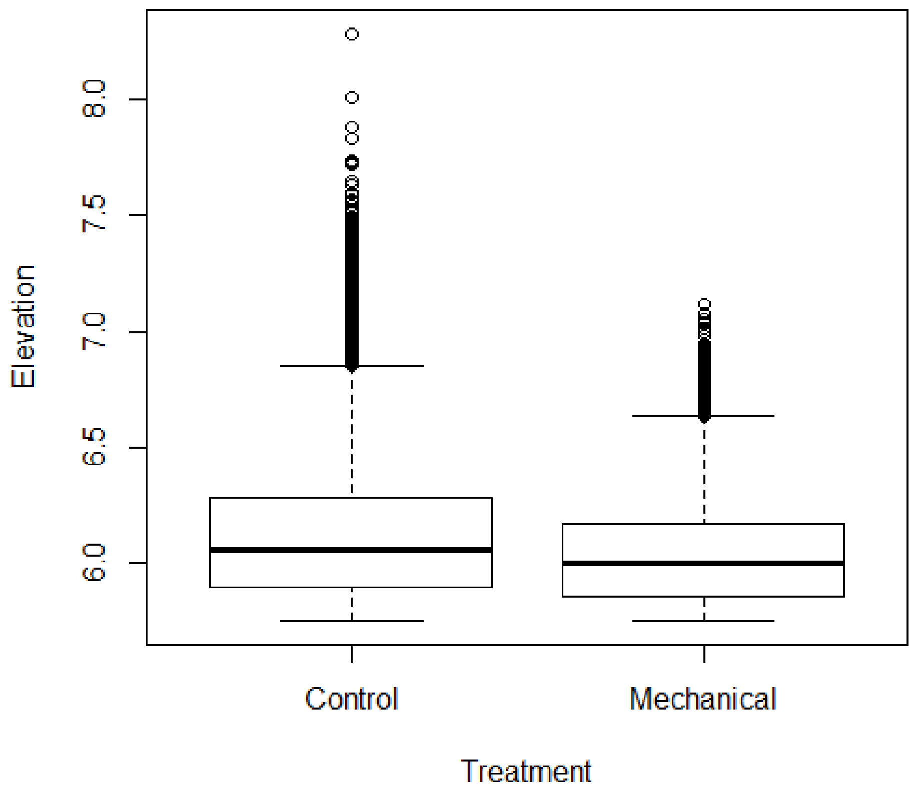


Figure 16. Foredune elevation (m) for control and mechanical treatment areas at Little River in March 2018. Dots are outliers.

# DISCUSSION

## Vegetation Analysis

My study demonstrated that the treatment of *A. arenaria* by either manual or mechanical removal was effective at lowering the cover of the targeted invasive species. The overall decrease in *A. arenaria* cover was similar between the treatments over time, with a larger decline from mechanical removal immediately following treatment. *Ammophila arenaria* cover was lower in mechanical removal areas compared to manual removal treatment areas at Gold Bluffs Beach, the only site where both removal techniques were used. However, the lowest cover of *A. arenaria* post-treatment was observed at Tolowa Dunes, which could be due to different pre-restoration conditions at the removal areas. Since I do not have pre-treatment data for the Tolowa Dunes site it is hard to compare to the levels of decreased *A. arenaria* at Gold Bluffs Beach. However, if the Tolowa Dunes' control area's average mean of *A. arenaria* cover is used as a substitution for pre-treatment conditions, then the estimated mean pre-treatment cover of *A. arenaria* would be similar to the other two sites, a cover class of 4 (10% - <25% cover). The decline in *A. arenaria* cover at Tolowa Dunes would then be greater than the decline in cover after removal at Little River and Gold Bluffs Beach for either removal treatment. Little River's cover class of *A. arenaria* in mechanical treatment areas decreased from the pre-removal of cover class of 4 to a post-treatment cover class of 1 (>0-<1% of overall cover). This suggests that both treatments have a similar effectiveness in lowering its target species cover to a cover class of 1. Since this before and after *A. arenaria* cover analysis relies on categorical cover class data, the results could be over-simplifying the nuanced changes in *A. arenaria* cover.

There were changes in *A. arenaria* cover in untreated areas at Gold Bluffs Beach during the study period. It is of note that *A. arenaria* cover decreased in control areas at Gold Bluffs Beach, and this decrease could be a factor that contributed to lower *A. arenaria* cover in the treatment areas. This decrease in *A. arenaria* in untreated control areas may be due to sand movement at the beach, as I recorded higher open sand in all treatment types in 2017 than was record in 2012 to 2014. There are a number of mechanisms that may be responsible for the loss of *A. arenaria* cover and increased sand at Gold Bluffs Beach. Gold Bluffs Beach has the highest acreage treated compared to the other sites (Forys et al. 2009, Transou 2012, Wisehart 2012, Mills 2015). With more opportunity for sand movement without *A. arenaria* to stabilize the dunes, there is a potential for more open sand, even further down the beach in the southern control areas. The beach may have seen more sediment loads from its many creeks that feed into the beach. In contrast, Tolowa Dunes has the opening of Lake Tolowa nearby and Littler River sediment is feed by the Little River and Mad River (Pickart and Sawyer 1998, Vaughan 2015). Gold Bluffs Beach has six small creeks that flow through the beach and into the Pacific Ocean (Mills 2015). If either the higher availability of open sand within a larger treatment area or more sediment outflow from creeks are responsible for lowering the *A. arenaria* cover in the control area, it would call into question mechanical being the most effective removal method to lower *A. arenaria* cover, due to these confounding factors at my study sites.

Changes in diversity of non-native plants over time differed among the three sites. Both treatments at Gold Bluff Beach lowered non-native diversity. The post-treatment non-native Shannon's diversity index was not statistically different between the two treatments at Gold Bluffs Beach. However, the pre-treatment Shannon's diversity index for non-natives in mechanical plots was higher than in the manual plots. This shows that mechanical removal can have a greater effect in decreasing of diversity of non-natives compared to manual removal. At Little River, the non-native Shannon's diversity index in the control plots decreased, indicating that other factors may be at play in lowering the diversity of non-natives over time. However, mechanical removal still decreased the Shannon's diversity index of non-natives to a greater degree than the control area's diversity was lowered. At Tolowa Dunes, non-native Shannon's diversity index was not significantly different between control and manual plots. This suggests that manual treatment is not targeting other non-native species, whereas mechanical can treat multiple species at once. Moreover, all three sites' removal treatment areas had lower or the same diversity of non-natives compared to pre-treatment measurements, indicating that restoration efforts are not increasing non-natives by increasing disturbance which non-natives thrive on (Pickart and Sawyer 1998, D'Antonio, and Meyerson 2002). In the control areas at Gold Bluffs Beach, non-native diversity did not increase and at Little River non-native diversity decreased, which could indicate that the removal treatments may play a more limited role in lowering the diversity of non-native species, if non-natives diversity is decreasing on its own.

Native diversity did not generally increase over time following removal of *A. arenaria*. Native diversity decreased significantly in mechanical removal areas at Gold Bluffs Beach, whereas both manual removal and control areas show no change in native's Shannon's diversity index post-treatment. This indicates a larger negative impact on natives from mechanical removal at Gold Bluffs Beach. At Little River, native diversity stayed the same in mechanical removal and control areas over time, which was fairly low at both time steps and in both areas. At Tolowa Dunes, manual removal appears to have increased native diversity compared to adjacent untreated areas. However, without pre-treatment data at Tolowa Dunes it is difficult to determine if there was a change in native plant diversity following the restoration. If the adjacent control site's native diversity levels are used as a proxy for pre-treatment diversity of the manual removal area, then Tolowa Dunes is the only site with increased native diversity after the removal of *A. arenaria*. With different environmental conditions at each beach, and varying changes to the control area's diversity, it is difficult to discern how large of an effect the removal methods are having on native diversity. Although there is evidence that mechanical removal is lowering the plant diversity at Gold Bluffs Beach and not increasing native diversity at Littler River. Manual removal can better serve restoration goals by not causing a similar decline to native plants (Pickart and Sawyer 1998). However, without suitable comparisons for uninvaded sites along the North Coast, it is hard to know what amount of native plant cover and diversity there was prior to the invasion of *A. arenaria* (Pickart 2016, personal communication).

This study found some degree of difference in plant taxonomic composition and cover between control and treatment plot cover for all three sites (Figure 10, Figure 11, and Figure 12). At Gold Bluffs Beach, the perMANOVA showed manual and mechanical plots differed in their community composition from the control plots. However, treatment did not explain all the variation between the groups' differences. This could be due to many plots with high open sand cover and little vegetation cover of any kind found in mechanical, manual and control areas. Control cover at Little River was different from mechanical cover and this difference explains a larger amount of the data than at Gold Bluffs Beach. This difference may be a representation of the lack of diversity in the mechanical plots measured by the Shannon's diversity index (Figure 8, Figure 11). The difference could also be due to high open sand cover in mechanical plots compared to control. Manual and control cover at Tolowa Dunes were different from each other as shown in the perMANOVA (Figure 12). The difference between the groups doesn't explain a lot of the variance. The difference measured could be accounted for by the higher diversity of natives, and more open sand in the manual areas than the control areas (Figure 9). Control plots' cover varied from treatment cover at all the sites surveyed.

Non-vegetation cover had associations with different treatment areas in the NMDS plots for all sites. Litter at all sites was higher in control areas. This could mean that sand is not moving as readily so it cannot bury litter as would be expected in a dynamic system. Biogenic soil crust, which is comprised of cyanobacteria, lichens, mosses and other organisms, had an association with control areas at Tolowas Dunes. This could indicate that the more stabilized invaded sites without disturbance from treatment was able to support more crust. Increased crust could help native bees that nest in the crust (Gordon 2000). However, the crust could also be a symptom of invasion and lack of disturbance on the dunes, as Tolowa is considered to be a highly invaded site (Pickart and Sawyer 1998). Cobble had a very low percentage cover in the plots surveyed and was associated with both mechanical and manual removal types at Gold Bluffs Beach and Tolowa Dunes. The presence of cobble or stones can play an important role in camouflage for plover chicks during brooding, and for the eggs during nesting (Hardy and Colwell 2012). Shell was more associated with treated areas than control areas at Little River and Tolowa dunes, which again plays an important role in camouflage for plovers (Zarnetske et al. 2010). The combination of increased shell and rocks cover could increase the chances of plover survival to fledging (Zarnetske et al. 2010, Hardy and Colwell 2012). However, it is of note that the plover population at Golds Bluffs Beach and Tolowa Dunes is small, with less than 6% of the breeding population at those two sites combined in the last 5 years (CSPNCRD 2017, Feucht et al. 2017). Only one plover nest was established at each of those beaches in 2017, and they both failed (CSPNCRD 2017, Feucht et al. 2017). Little River has a larger plover population with 4 males and 4 females inhabiting the beach, with 6 nests established in 2017 between them (CSPNCRD 2017). In 2017 at Little River, two of the three plover chicks that hatched were able to successfully fledge (CSPNCRD 2017). Past reproductive success of plovers in these areas is traditionally low (Feucht et al. 2017). When the adjacent North Clam Beach area is included with Little River statistics, the site has a total breeding efficiency (i.e., the total number of fledged chicks by total number of eggs laid) of 0.05 since 2001 (CSPNCRD 2017, Feucht et al. 2017). Overall, the restoration areas have yet to be highly utilized by the plovers, and has thus far not afforded them a relief from population decline.

## Dune Morphology

At Gold Bluffs Beach, the difference in highest foredune elevation between control and treated areas was greater than at Little River. Overall, however, the trend at both sites was the same: in mechanical treated areas, the foredune was lower in elevation than adjacent control areas (Figure 14 and Figure 16). The DEM does include the height of the plants photographed, which means that *A. arenraia* at a height of 0.5 to 1.2 m, which could account for the added elevation in control areas (Baldwin et al. 2012). Of note, the shape of the foredune differed at Little River between control and mechanical areas, which have low dune hummocks rather than the linear tall foredunes in control areas that is common in *A. arenaria* invasion (Hilton et al. 2005). The different areas surveyed were not controlled for geographical location differences. At Gold Bluffs Beach, a creek flows through the control area, which may have skewed the elevation results, by adding and shifting sediment to create the higher foredune and lowering the southern end of the foredune at the mouth of the creek. Since the restoration work examined in this study focused primarily on the nearshore dunes area, to allow for a gradual change to the back dunes which protects roads and other areas from sand movement, it is less clear what the removal of *A. arenaria* is doing to the back dune areas

(Forys, et al. 2009). The back dune is still invaded with *A. arenaria*, and other invasive non-native species such as *Lupinus arboreus* (yellow bush lupine). Native trees such as *Picea sitchensis* (Sitka spruce) have also encroached onto the back dune area, which would not be historically found in dune hollow ecosystem (Pickart and Sawyer 1998, Forys 2015).

## Management Recommendations

This study examined impacts of *A. arenaria* removal over several increments of time. Additional long-term studies to determine the movement and shape of the dunes over time can provide valuable data on how the dunes are responding not only to restoration work, but also to El Niño, sea level rise, and human development (Lithgow et al. 2013, FD 2015). Future study with the use of UAV images of dunes could inform decisions for the best long-term dune management for coastal community's protection by giving up-to-date and easily available elevation data. As well, UAV images could be an alternative to waiting for USDA or NOAA LIDAR fly overs (Vaughan 2015).

Overall, there are pros and cons to manual and mechanical treatment of *A. arenaria*. Mechanical removal decreased the cover of *A. arenaria* the greatest, and can decrease all other non-native cover and diversity as well. Mechanical removal is a quicker and more cost-effective removal method compared to manual removal (Peterson, B. 2004, Parsons and Minnick 2015). Mechanical removal has been shown to lower the foredune elevation, which is a desired result for coastal sand dune ecosystem recovery

(Pickart and Sawyer 1998, Pickart 2008). However, mechanical removal can cause a decrease in biodiversity of both natives and non-natives. Other studies have found that it may be harder for natives to grow back after mechanical removal is used with other removal methods, such as pesticide, and manual mowing, because it may compact and affect the free movement of sand (Zarnetske et al. 2010). In contrast, manual removal causes less disturbance on the dune habitat and leads to a higher native plant cover than mechanical removal. However, manual removal also leads to higher non-native plant diversity and cover. If other non-native species are targeted during manual removal, with crews that are trained and equipped to remove other non-natives, then other non-native cover could be reduced more effectively. Mean *A. arenaria* cover class following manual treatment was comparable to mechanical post-removal cover class over time. Manual removal also has disadvantages such as a higher price tag and a longer time until *A. arenaria* cover is low enough to stop retreatment (Pickart and Sawyer 1998, Peterson 2004.). However, a switch to using more volunteer labor for manual removal may cut costs significantly, but can slow down the restoration timeline (Pickart and Sawyer 1998).

Further study could expand land mangers' knowledge of the long term-effects of removal treatments. A study comparing other treatment methods to remove *A. arenaria*, such as fire, pesticides, mowing, and salt water inundation could compare cost and effectiveness of these methods (Pickart and Sawyer 1989, Moore and Davis 2004, Peterson 2004, Hyland and Holloran 2005). In addition, studying combined methods effectiveness for a long period of time could improve restoration work. Setting up study areas with treatments of equal size for the different treatments would also help eliminate bias in the experiment. Also, the effect of planting or seeding natives in conjunction with removal should be studied in the long term as well. However, these landscapes are not experiments, they are working landscapes used by the public for recreation, and California State Parks have set goals to preserve them as well as allow public use (CSP 2018). Any restoration efforts and experiments done on them need to consider these goals.

Which *A. arenaria* removal method is more effective will depend on the management goals for the land. If the target species is the only concern of the restoration project, then mechanical will be the best fit to lower *A. arenaria* cover. Also, if funds are limited for the restoration, mechanical is more cost-effective for removal. However, if one is concerned with the loss of native biodiversity, then the results of this study indicate that manual removal will afford better results in the long run. In a time when global biodiversity is being lost, and is only projected to continue to decline, manual removal has the distinct advantage of helping restore native coastal sand dune species (Pereira et al. 2010, Barnosky et al. 2011). Coastal sand dunes in California contain sensitive and endemic species (Pickart and Sawyer 1989). This study was conducted within the California Floristic Province, one of the global diversity hot spots in the world, where preserving species diversity is particularly important in this unique habitat (Myers et al. 2000). Unfortunately, invasive species such as *A. arenaria* may not be easily eradicated within a decade or more of restoration work, or may never be fully eradicated from a site due to recruitment from nearby invaded areas (Pickart and Sawyer 1989, D'Amtonio and Meyerson 2002, Norton 2009). With this in mind, manual removal of *A. arenaria* will help preserve native biodiversity and continue to lower the invasive target species cover over the long term.

# LITERATURE CITED

Anderson, M. 2001. A new method for non-parametric multivariate analysis of variance. *Austral Ecology*, 26(1): 32-46.

Baldwin, B., Goldman, D., Keil, D., Patterson, R., Rosatti, T., Wilken, D., Greenhouse, J., Markos, S., Moe, R.L., Simono, S., Wetherwax, M., and Vorobik, L.A. 2012. *The Jepson manual: Vascular plants of California* (2nd ed.). Berkeley, Calif.: University of California Press.

Barnosky, A. D., Matzke, N., Tomiya, S., Wogan, G. O. U., Swartz, B., Quental, T. B., Marshall, C., McGuire, J.L., Lindsey, E.L., Maguire, K.C., Mersey, B., & Ferrer, E. A. (2011). Has the earth's sixth mass extinction already arrived? *Nature*, 471(7336): 51-57.

Belnap, J., & Lange, O. 2001. Biological soil crusts: Structure, function, and management. *Ecological studies*, 150. New York: Springer.

Braun-Blanquet, J., Fuller, G.D. & Conard, H.S. 1932. Plant Sociology: The Study of Plant Communities (1st ed). New York, London: McGraw-Hill Book Co.

Buell, A. C., Pickart, A. J., & Stuart, J. D. 1995. Introduction History and Invasion Patterns of *Ammophila arenaria* on the North Coast of California. *Conservation Biology*, 9 (6): 1587-1593.

[CSP] California State Parks. c2018. About Us. Sacramento, CA: State of California; [accessed 2018 May 2]. https://www.parks.ca.gov/?page_id=91

[CSPNCRD] California State Parks North Coast Redwoods District. 2015. North Coast Redwoods District Western Snowy Plover Annual Report 2013/2014. California State Parks, North Coast Redwoods District. Eureka, CA: California State Parks.

[CSPNCRD] California State Parks North Coast Redwoods District. 2017. North Coast Redwoods District Western Snowy Plover Annual Report 2016/2017. California State Parks, North Coast Redwoods District. Eureka, CA: California State Parks.

D'Antonio, C., & Meyerson, L. 2002. Exotic plant species as problems and solutions in ecological restoration: A synthesis. *Restoration Ecology*, 10(4): 703-713.

Dinno, A. 2017. dunn.test: Dunn's Test of Multiple Comparisons Using Rank Sums. R package version 1.3.5. https://CRAN.R-project.org/package=dunn.test

Dunn, O. 1964. Multiple Comparisons Using Rank Sums. *Technometrics*, 6(3): 241-252.

Esri. 2009. World Imagery [basemap]. Scale Not Given. Source for base layer: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.https://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer

Feucht, E.J., Colwell1, M.A., Orluck, D.J., Papian, N.C., Raby, K.M. & McAllister S.E. 2017. Final Report: 2017 Snowy Plover Breeding in Coastal Northern California, Recovery Unit 2. Submitted to U.S. Fish and Wildlife Service, Arcata, California, USA.

[FD] Friends of the Dunes. 2015. Dunes Climate Ready Study. Arcata, CA: Friends of the Dunes [accessed 2018 May 2]. http://www.friendsofthedunes.org/science/climate-ready/

Forys, M. 2015. Little River State Beach Nearshore Dunes Restoration Project Summary Report. California State Parks, North Coast Redwoods District. Eureka, CA: California State Parks.

Forys, M., Transou, A., Beers, D., & Vaughan, P. 2009. Little River State Beach Restoration and Enhancement Plan. California State Parks, North Coast Redwood District. Eureka, CA: California State Parks.

Gordon, D.M. 2000. Plants as indicators of leafcutter bee (Hymenoptera: Megachilidae) nest habitat in coastal dunes. *Pan-Pacific Entomologist* 76:219-233.

Hardy, M. A., & Colwell, M. A. 2012. Factors Influencing Snowy Plover Nest Survival on Ocean- Fronting Beaches in Coastal Northern California. *Waterbirds*, 35(4): 503-656.

Hart, A. T., Hilton, M. J., Wakes, S. J., & Dickinson, K. J. 2012. The Impact of *Ammophila arenaria* Foredune Development on Downwind Aerodynamics and Parabolic Dune Development. *Journal of Coastal Research*, 28(1): 112-122.

Hilton, M., Duncan, M., & Jul, A. 2005. Processes of *Ammophila arenaria* (Marram Grass) invasion and indigenous species displacement, Stewart Island, New Zealand. *Journal of Coastal Research*, 21(1): 175-185.

Hobbs, R. J., & Harris, J. A. 2001. Restoration Ecology: Repairing the Earth's Ecosystems in the New Millennium. *Restoration Ecology*, 9(2): 239–246.

Huiskes, A.H. 1979. Biological Flora of the British Isles. *Journal of Ecology*, 67(1): 363-382.

Hyland, T., & Holloran, P. 2005. Controlling European beachgrass (*Ammophila arenaria*) using prescribed burns and herbicide. *Chico, CA: Cal-IPC (California Invasive Plant Council).*

Lithgow, D., Martínez, M. L., Gallego-Fernández, J. B., Hesp, P. A., Flores, P., Gachuz, S., Rodríguez-Revelo, N., Jiménez-Orocio, O., Mendoza-González, G., Álvarez-Molina, L. L. 2013. Linking Restoration Ecology with Coastal Dune Restoration. *Geomorphology,* 199: 214-224.

Mancini, F., Dubbini, M., Gatt, M., Stecchi, F., Fabbri, S., & Gabbianelli, G. 2013. Using Unmanned Aerial Vehicles (UAV) for High-Resolution Reconstruction of Topography: The Structure from Motion Approach on Coastal Environments. *Remote Sensing,* 5: 6880-6898.

Mascarenhas, A., & Jayakumar, S. 2008. An Environmental Perspective of Post-Tsunami Scenario Along the Coast of Tamil Nadu, India: Role of Sand Dunes and Forests. *Journal of Environmental Management,* 89(1): 24-34.

McDonald, K. 2015. Differences in the Morphology of Restored and Invaded Foredunes. U.S. Fish and Wildlife Service. Arcata, CA: U.S. Fish and Wildlife Service.

Mills, A. 2015. Evaluating the Effects of Mechanical and Manual Removal of *Ammophila arenaria* within Coastal Dunes of Humboldt County. Thesis, California State University Chico, Chico, CA, USA.

Moore, P., & Davis, A. 2004. Marram grass *Ammophila arenaria* removal and dune restoration to enhance nesting habitat of Chatham Island oystercatcher Haematopus chathamensis, Chatham Islands, New Zealand. *Conservation Evidence,* 1: 8-9.

Muir, J. J., & Colwell, M. A. 2010. Snowy Plovers Select Open Habitats for Courtship Scrapes and Nests. *The Condor,* 112(3): 507-510.

Myers, N., Mittermeier, R., Mittermeier, C., & Kent, J. 2000. Biodiversity hotspots for conservation priorities. *Nature,* 403(6772): 853-8.

Oksanen, J., Guillaume Blanchet, F., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R. B., Simpson, G.L., Solymos, P., Henry, M., Stevens, H., Szoecs E., &Wagner, H. 2018. vegan: Community Ecology Package. R package version 2.5-1. https://CRAN.R-project.org/package=vegan

Parsons, L. & Minnick, S. 2015. Coastal Dune Restoration Environmental Assessment. National Park Service, Point Reyes National Seashore. Point Reyes, CA: National Park Service.

Pereira, H.M., Leadley, P.W., Proença, V., Alkemade, R., Scharlemann, J.P., Fernandez-Manjarrés, J.F., Araújo, M.B., Balvanera, P., Biggs, R., Cheung, W.W. and Chini, L. 2010. Scenarios for global biodiversity in the 21st century. *Science,* 330(6010): 1496-1501.

Peterson, B. 2004. The Use of Heavy Machinery (Excavators) to Remove *Ammophila arenaria* (European beachgrass) from Native Sand Dunes at Point Reyes National Seashore. *In,* C. Pirosko, (ed.). *2004 Symposium Proceedings California Invasive Plant Council Symposium,* 8: 59-61.

Pickart, A. 1997. Control of European Beachgrass (*Ammophila arenaria*) on the West Coast of the United States. *1997 Symposium Proceedings, California Exotic Pest Plant Council.*

Pickart, A. 2008. Restoring the Grasslands of Northern California's Coastal Dunes. *Grasslands*, 18(1): 1-9.

Pickart, A. J., & Barbour, M. G. 2007. Beach and Dune. In M. Barbour, T. Keeler-Wolf, & A. A. Schoenherr, *Terrestrial Vegetation of California* (3rd ed.). Berkeley Los Angeles London: University of California Press. p. 155-173.

Pickart, A.J. & Sawyer, J.O. 1998. *Ecology and Restoration of Northern California Coastal Dunes*. Sacramento, CA: California Native Plant Society.

Pimentel, D., Lach, L., Zuniga, R., & Morrison, D. 2000. Environmental and Economic Costs of Nonindigenous Species in the United States. *BioScience*, 50(1): 53-65.

[SER] Society of Ecological Restoration Science and Policy Working Group. 2004. The SER International Primer on Ecological Restoration Ver. 2. Tucson Arizona: Society for Ecological Restoration International.

[TIGER] Topologically Integrated Geographic Encoding and Referencing. 2016. California County boundaries. https://data.ca.gov/dataset/ca-geographic-boundaries/resource/091ff50d-bb24-4537-a974-2ce89c6e8663

Transou, A. 2012. North Gold Bluff Beach Coastal Dune Redwood Plan Prairie Creek Redwood State Park. California State Parks, North Coast Redwood District. Eureka, CA: California State Parks.

Vaughan, P. R. 2015. Geological Monitoring Report 2005-20015 Little River State Beach Exotic Vegetation Removal. California State Parks, North Coast Redwoods District. Eureka, CA: California State Parks.

Wentworth, C. 1922. A Scale of Grade and Class Terms for Clastic Sediments. The *Journal of Geology*, 30(5): 377-392.

Wiedemann, A. M. 1984. The Ecology of Pacific Northwest Coastal Sand Dunes: A Community Profile. U.S. Department of the Interior and U.S. Department of the Army, US Fish and Wildlife and Army Corps of Engineers. Olympia, WA: fish and Wildlife Service U.S, Department of the Interior.

Wiedemann, A. M., & Pickart, A. 1996. The *Ammophila* Problem on the Northwest Coast of North America. *Landscape and Urban Planning*, 34: 287-299.

Wilcove, D. S., Rothstein, D., Dubow, J., Phillips, A., & Losos, E. 1998. Quantifying Threats to Imperiled Species in the United States. *BioScience*, 48 (8): 607-615.

Wisehart, L. 2012. European Beachgrass Removal at Tolowa Dunes State Parks. California State Parks, North Coast Redwoods District. Eureka, CA: California State Parks.

Zarnetske, P. L., Seabloom, E. W., & Hacker, S. D. 2010. Non-target Effects of Invasive Species Management: Beachgrass, Birds, and Bulldozers in Coastal Dunes. *Ecosphere,* 1(5): 1-20.

Zavaleta, E. S., Hobbs, R. J., & Mooney, H. A. 2001. Viewing Invasive Species Removal in a Whole-Ecosystem Context. *TRENDS in Ecology & Evolution,* 16(8): 454-459.

# APPENDIX A

Appendix A: Plant species found during vegetation surveys, native status (Y for yes, and N for no), family, CNPS rare plant status and Cal IPC rating.

| Scientific Name | Common Name | Native | Family | CNPS | Cal IPC rating |
|---|---|---|---|---|---|
| ***Abronia latifolia*** | yellow sand verbena | Y | Nyctaginaceae | | |
| ***Abronia umbellata* var. *breviflora*** | pink sand verbena | Y | Nyctaginaceae | 1B.1 | |
| ***Achillea millefolium*** | yarrow | Y | Asteraceae | | |
| ***Acmispon glaber*** | deerweed | Y | Fabaceae | | |
| ***Aira caryophyllea*** | silver hair grass | N | Poaceae | | |
| ***Aira praecox*** | Yellow hairgrass | N | Poaceae | | |
| ***Alnus rubra*** | red alder | Y | Betulaceae | | |
| ***Ambrosia chamissonis*** | beach bur | Y | Asteraceae | | |
| ***Ammophila arenaria*** | European beachgrass | Y | Poaceae | | High |
| ***Anaphalis margaritacea*** | pearly everlasting | Y | Asteraceae | | |
| ***Angelica hendersonii*** | coast angelica | Y | Apiaceae | | |
| ***Anthoxanthum odoratum*** | sweet vernal grass | N | Poaceae | | Limited |
| ***Anthoxanthum odoratum*** | sweet vernal grass | N | Poaceae | | Limited |
| ***Armeria maritima*** | Thrift seapink | Y | Plumbaginaceae | | |
| ***Artemisia pycnocephala*** | Coastal sagewort | Y | Asteraceae | | |
| ***Baccharis pilularis*** | coyote bush | Y | Asteraceae | | |
| ***Bellis perennis*** | English daisy | N | Asteraceae | | |
| ***Brassica nigra*** | black mustard | N | Brassicaceae | | Moderate |
| ***Briza maxima*** | rattlesnake grass | N | Poaceae | | Limited |
| ***Bromus carinatus*** | California Brome | Y | Poaceae | | |
| ***Cakile maritima*** | sea rocket | N | Brassicaceae | | Limited |
| ***Calystegia soldanella*** | beach morning-glory | Y | Convolvulaceae | | |
| ***Camissoniopsis cheiranthifolia*** | beach evening-primrose | Y | Onagraceae | | |

| Scientific Name | Common Name | Native | Family | CNPS | Cal IPC rating |
|---|---|---|---|---|---|
| ***Cardamine hirsuta*** | bitter-cress | N | Brassicaceae | | |
| ***Cardionema ramosissimum*** | sand mat | Y | Caryophyllaceae | | |
| ***Carex obnupta*** | slough sedge | Y | Cyperaceae | | |
| ***Carex pansa*** | sand-dune sedge | Y | Cyperaceae | | |
| ***Carex sps.*** | sedge | | Cyperaceae | | |
| ***Cerastium* sp.** | mouseear chickweed | | Caryophyllaceae | | |
| ***Cirsium vulgare*** | bull thistle | N | Asteraceae | | Moderate |
| ***Claytonia* sp.** | minors lettuce | | Montiaceae | | |
| ***Cortaderia jubata/selloana*** | jubata/pampass grass | N | Poaceae | | High |
| ***Cotula coronopifolia*** | brass buttons | N | Asteraceae | | Limited |
| ***Cynosurus echinatus*** | dogtail grass | N | Poaceae | | Moderate |
| ***Cytisus scoparius*** | scotch broom | N | Fabaceae | | High |
| ***Dipsacus fullonum*** | wild teasel | N | Dipsacaceae | | Moderate |
| ***Distichlis spicata*** | salt grass | Y | Poaceae | | |
| ***Dudleya farinosa*** | bluff lettuce | Y | Crassulaceae | | |
| ***Dysphania ambrosioides*** | Mexican Tea | N | Chenopodiaceae | | |
| ***Elymus mollis* subsp. *mollis*** | American dune grass | Y | Poaceae | | |
| ***Erechtites* sp.** | burnweed | N | Asteraceae | | |
| ***Erigeron canadensis*** | horseweed | Y | Asteraceae | | |
| ***Erigeron glaucus*** | seaside daisy | Y | Asteraceae | | |
| ***Eriogonum latifolium*** | Coast buckwheat | Y | Polygonaceae | | |
| ***Festuca bromoides*** | Brome fescue | N | Poaceae | | |
| ***Festuca microstachys*** | annual fescue | Y | Poaceae | | |
| ***Festuca myuros*** | rattail fescue | N | Poaceae | | Moderate |
| ***Fragaria chiloensis*** | beach strawberry | Y | Rosaceae | | |
| ***Galium aparine*** | goose grass | Y | Rubiaceae | | |
| ***Gamochaeta ustulata*** | purple cudweed | Y | Asteraceae | | |
| ***Glehnia littoralis* subsp. *leiocarpa*** | glehnia | Y | Apiaceae | | |
| ***Grindelia stricta*** | Coastal gumweed | Y | Asteraceae | | |
| ***Holcus lanatus*** | velvet grass | N | Poaceae | | Moderate |

| Scientific Name | Common Name | Native | Family | CNPS | Cal IPC rating |
|---|---|---|---|---|---|
| ***Hypericum perforatum* subsp. *perforatum*** | klamathweed | N | Clusiaceae | | Limited |
| ***Hypochaeris glabra*** | smooth cat's car | N | Asteraceae | | Limited |
| ***Hypochaeris radicata*** | rough cat's ear | N | Asteraceae | | Moderate |
| ***Isatis tinctoria*** | woad | N | Brassicaceae | | Moderate |
| ***Juncus breweri*** | Brewer's rush | Y | Juncaceae | | |
| ***Juncus bufonius*** | toad rush | Y | Juncaceae | | |
| ***Juncus falcatus*** | sickleleaved rush | Y | Juncaceae | | |
| ***Juncus* sp.** | rush | | Juncaceae | | |
| ***Kickxia elatine*** | sharpleaf cancerwort | N | Plantaginaceae | | |
| ***Lathyrus japonicus*** | seaside pea | Y | Fabaceae | 2B.1 | |
| ***Lathyrus littoralis*** | beach pea | Y | Fabaceae | | |
| ***Linaria dalmatica* subsp. *dalmatica*** | Dalmatian toadflax | N | Plantaginaceae | | Moderate |
| ***Linum bienne*** | flax | N | Linaceae | | |
| ***Lotus corniculatus*** | bird foot treefoil | N | Fabaceae | | |
| ***Lupinus arboreus*** | bush lupine | Y/N | Fabaceae | | Limited |
| ***Lysimachia arvensis*** | scarlet pimpernel | N | Myrsinaceae | | |
| ***Lythrum hyssopifolia*** | loosestrife | N | Lythraceae | | |
| ***Melilotus albus*** | white sweetclover | N | Fabaceae | | |
| ***Mentha pulegium*** | pennyroyal | N | Lamiaceae | | Moderate |
| ***Morella californica*** | wax myrtle | Y | Myricaceae | | |
| ***Phacelia argentea*** | sanddune phacelia | | Hydrophyllaceae | 1B.1 | |
| ***Picea sitchensis*** | Sitka spruce | Y | Pinaceae | | |
| ***Pinus contorta*** | beach pine | Y | Pinaceae | | |
| ***Plantago lanceolata*** | English plantain | N | Plantaginaceae | | Limited |
| ***Plantago major*** | common plantain | N | Plantaginaceae | | |
| ***Poa annua*** | annual blue grass | N | Poaceae | | |
| ***Poa confinis*** | beach blue grass | Y | Poaceae | | |

| **Scientific Name** | **Common Name** | **Native** | **Family** | **CNPS** | **Cal IPC rating** |
|---|---|---|---|---|---|
| ***Poa douglasii*** | sand dune blue grass | Y | Poaceae | | |
| ***Poa macrantha*** | seashore blue grass | Y | Poaceae | | |
| ***Poa trivialis*** | rough blue grass | N | Poaceae | | |
| ***Polycarpon tetraphyllum*** | Four-leaved polycarp | N | Caryophyllaceae | | |
| ***Polygonum aviculare*** | common knotweed | N | Polygonaceae | | |
| ***Polygonum paronychia*** | dune knotweed | Y | Polygonaceae | | |
| ***Polypodium scouleri*** | leather-leaf fern | Y | Polypodiaceae | | |
| ***Polypodium sps.*** | fern | | Polypodiaceae | | |
| ***Polypogon monspeliensis*** | Rabbitsfoot grass | N | Poaceae | | Limited |
| ***Potentilla anserina* ssp. *pacifica*** | silverweed cinquefoil | Y | Rosaceae | | |
| ***Pseudognaphalium californicum*** | ladies tobacco | Y | Asteraceae | | |
| ***Pseudognaphalium stramineum*** | cottonbatting plant | Y | Asteraceae | | |
| ***Pseudotsuga menziesii*** | Douglas-fir | Y | Pinaceae | | |
| ***Rumex acetosella*** | sheep sorrel | N | Polygonaceae | | Moderate |
| ***Rumex conglomeratus*** | clustered dock | N | Polygonaceae | | |
| ***Rumex crispus*** | curly dock | N | Polygonaceae | | Limited |
| ***Rumex salicifolius*** | willow dock | Y | Polygonaceae | | |
| ***Rumex* sp.** | dock | | Polygonaceae | | |
| ***Salix* sp.** | willow | | Salicaceae | | |
| ***Sanicula* sp.** | sanicle | Y | Apiaceae | | |
| ***Senecio glomeratus*** | cutleaf burnweed | N | Asteraceae | | Moderate |
| ***Senecio minimus*** | coastal burnweed | N | Asteraceae | | |
| ***Silene gallica*** | wind-mill pink | N | Caryophyllaceae | | |
| ***Sonchus oleraceus*** | common sow thistle | N | Asteraceae | | |
| ***Symphyotrichum chilense*** | aster | Y | Asteraceae | | |
| ***Tanacetum bipinnatum*** | dune tansy | Y | Asteraceae | | |

| Scientific Name | Common Name | Native | Family | CNPS | Cal IPC rating |
|---|---|---|---|---|---|
| ***Trifolium* sp.** | clover | | Fabaceae | | |
| ***Trifolium wormskioldii*** | cow clover | Y | Fabaceae | | |
| ***Vaccinium ovatum*** | California huckleberry | Y | Ericacae | | |
| ***Vicia gigantea*** | giant vetch | Y | Fabaceae | | |
| ***Vicia sativa*** | vetch | N | Fabaceae | | |

**Definitions for California Native Plant Society Rare Plant Ranks and Threat Ranks**
*California Native Plant Society*
Rare Plant Rank
Plants rare, threatened, or endangered in California and elsewhere

1B-Plants rare, threatened, or endangered in California and elsewhere
Plants with a California Rare Plant Rank of 1B are rare throughout their range with the majority of them endemic to California. Most of the plants that are ranked 1B have declined significantly over the last century. California Rare Plant Rank 1B plants constitute the majority of taxa in the CNPS Inventory, with more than 1,000 plants assigned to this category of rarity
All of the plants constituting California Rare Plant Rank 1B meet the definitions of the California Endangered Species Act of the California Fish and Game Code, and are eligible for state listing. Impacts to these species or their habitat must be analyzed during preparation of environmental documents relating to CEQA, or those considered to be functionally equivalent to CEQA, as they meet the definition of Rare or Endangered under CEQA Guidelines §15125; (c) and/or §15380.
.
2B- Plants rare, threatened, or endangered in California but more common elsewhere
Except for being common beyond the boundaries of California, plants with a California Rare Plant Rank of 2B would have been ranked 1B. From the federal perspective, plants common in other states or countries are not eligible for consideration under the provisions of the Federal Endangered Species Act. With California Rare Plant Rank 2B, we recognize the importance of protecting the geographic range of widespread species. In this way we protect the diversity of our own state's flora and help maintain evolutionary processes and genetic diversity within species.
All of the plants constituting California Rare Plant Rank 2B meet the definitions of the California Endangered Species Act of the California Fish and Game Code, and are eligible for state listing. Impacts to these species or their habitat must be analyzed during preparation of environmental documents relating to CEQA, or those considered to be functionally equivalent to CEQA, as they meet the definition of Rare or Endangered under CEQA Guidelines §15125 (c) and/or §15380.

Threat Ranks

Ranks at each level also include a threat rank (e.g., CRPB 4.3) and are determined as follows:

- 0.1-Seriously threatened in California (over 80% of occurrences threatened / high degree and immediacy of threat)
- 0.2-Moderately threatened in California (20-80% occurrences threatened / moderate degree and immediacy of threat)
- 0.3-Not very threatened in California (less than 20% of occurrences threatened / low degree and immediacy of threat or no current threats known)

**Definitions for California Invasive Plant Council Weed Rating Categories**
*California Invasive Plant Council*
Weed Categories
Each plant on the list received an overall rating of High, Moderate or Limited based on evaluation using the criteria system.
High – These species have severe ecological impacts on physical processes, plant and animal communities, and vegetation structure. Their reproductive biology and other attributes are conducive to moderate to high rates of dispersal and establishment. Most are widely distributed ecologically.

Moderate – These species have substantial and apparent—but generally not severe—ecological impacts on physical processes, plant and animal communities, and vegetation structure. Their reproductive biology and other attributes are conducive to moderate to high rates of dispersal, though establishment is generally dependent upon ecological disturbance. Ecological amplitude and distribution may range from limited to widespread.

Limited – These species are invasive but their ecological impacts are minor on a statewide level or there was not enough information to justify a higher score. Their reproductive biology and other attributes result in low to moderate rates of invasiveness. Ecological amplitude and distribution are generally limited, but these species may be locally persistent and problematic.

# APPENDIX B

Appendix B: Gold Bluffs Beach's Dunn's test after Kruskal Wallis between each treatments, manual, mechanical and control, *Ammophila arenaria* cover for before removal (July 2012-January 2013), one year after removal (February 2014), and 4 years after removal (May and September 2017)(Bolded p-values are less than 0.05).

| | | **Control Before** | **Control 1 Year** | **Control 4 years (May)** | **Control 4 years (Sept.)** | **Manual Before** | **Manual 1 Year** | **Manual 4 Years (May)** | **Manual 4 Years (Sept.)** | **Mechanical Before** | **Mechanical 1 Year** | **Mechanical 4 Years (Sept.)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Control 1 Year** | Z score | -1.08 | | | | | | | | | | |
| | p-value | 0.15 | | | | | | | | | | |
| **Control 4 years (May)** | Z score | 9.33 | 10.46 | | | | | | | | | |
| | p-value | **0** | **0** | | | | | | | | | |
| **Control 4 years (Sept.)** | Z score | 7.99 | 9.15 | -1.66 | | | | | | | | |
| | p-value | **0** | **0** | 0.06 | | | | | | | | |
| **Manual Before** | Z score | 0.84 | 1.91 | -8.31 | -6.97 | | | | | | | |
| | p-value | 0.21 | **0.03** | **0** | **0** | | | | | | | |
| **Manual 1 Year** | Z score | 4.74 | 5.8 | -4.23 | -2.79 | 3.84 | | | | | | |
| | p-value | **0** | **0** | **0** | **0.0034** | **0.0001** | | | | | | |

| | | Control Before | Control 1 Year | Control 4 years (May) | Control 4 years (Sept.) | Manual Before | Manual 1 Year | Manual 4 Years (May) | Manual 4 Years (Sept.) | Mechanical Before | Mechanical 1 Year | Mechanical 4 Years (Sept.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Manual 4 years (May** | Z score | 11.97 | 13.08 | 3.01 | 4.7 | 10.94 | 6.95 | | | | | |
| | p-value | **0** | **0** | **0.0017** | **0** | **0** | **0** | | | | | |
| **Manual 4 years (Sept.)** | Z score | 13.36 | 14.47 | 4.34 | 6.09 | 12.29 | 8.24 | 1.24 | | | | |
| | p-value | **0** | **0** | **0** | **0** | **0** | **0** | 0.12 | | | | |
| **Mechanical Before** | Z score | -3.36 | -2.31 | -12.53 | -11.31 | -4.14 | -7.91 | -15.03 | -16.4 | | | |
| | p-value | **0.0005** | **0.0127** | **0** | **0** | **0** | **0** | **0** | **0** | | | |
| **Mechanical 1 Year** | Z score | 13.34 | 14.39 | 4.9 | 6.53 | 12.36 | 8.55 | 2 | 0.84 | 16.23 | | |
| | p-value | **0** | **0** | **0** | **0** | **0** | **0** | **0.03** | 0.21 | **0** | | |
| **Mechanical 4 years (May)** | Z score | 14.55 | 15.65 | 5.73 | 7.48 | 13.49 | 9.5 | 2.65 | 1.45 | 17.52 | 0.52 | |
| | p-value | **0** | **0** | **0** | **0** | **0** | **0** | **0.005** | 0.08 | **0** | 0.3 | |
| **Mechanical 4 Years (Sept.)** | Z score | 15.45 | 16.57 | 6.55 | 8.36 | 14.36 | 10.31 | 3.4 | 2.19 | 18.42 | 1.2 | 0.71 |
| | p-value | **0** | **0** | **0** | **0** | **0** | **0** | **0.0005** | **0.0171** | **0** | 0.12 | 0.24 |

# APPENDIX C

Appendix C: Tolowa Dune’s Dunn’s test after Kruskal Wallis between each treatments, manual and control, *Ammophila arenaria* cover for 7 year after treatment (in May and September) (bold p-values are less than 0.05).

| **Treatment** | **Time** | **Statistic** | **Control** | **Control** | **Manual** |
|---|---|---|---|---|---|
| | | | 7 Years (May) | 7 Years (Sept.) | 7 Years (May) |
| **Control** | 7 Years (Sept.) | Z test | -1.16 | | |
| | | p-value | 0.15 | | |
| **Manual** | 7 Years (May) | Z test | 8.03 | 9.18 | |
| | | p-value | **0.00** | **0.00** | |
| | 7 Years (Sept.) | Z test | 8.01 | 9.17 | 0.01 |
| | | p-value | **0.00** | **0.00** | 0.50 |

# APPENDIX D

Appendix D: Little River's Dunn's test after Kruskal Wallis between each treatments, control and mechanical, *Ammophila arenaria* cover for before treatment (2009), and one year (2010), 2 years (2011) and 8 years (May and September 2017) after removal  year after treatment (in May and September)(bolded p-values are less than 0.05).

| | | | **Control** | | | | | **Mechanical** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Before** | **1 Year** | **2 Years** | **8 Years (May)** | **8 years (Sept.)** | **Before** | **1 Year** | **2 Years** | **8 Years (May)** |
| **Control** | 1 Year | Z score | -1.01 | | | | | | | | |
| | | p-value | 0.18 | | | | | | | | |
| | 2 Years | Z score | -0.41 | 0.65 | | | | | | | |
| | | p-value | 0.38 | 0.29 | | | | | | | |
| | 4 Years (May) | Z score | -1.99 | -1.31 | -1.75 | | | | | | |
| | | p-value | **0.03** | 0.12 | 0.06 | | | | | | |
| | 4 years (Sept.) | Z score | -1.73 | -1.04 | -1.49 | 0.24 | | | | | |
| | | p-value | 0.06 | 0.18 | 0.09 | 0.43 | | | | | |
| **Mechanical** | Before | Z score | 2.74 | 3.98 | 3.33 | 4.02 | 3.8 | | | | |
| | | p-value | **0.0048** | **0.0001** | **0.0007** | **0.0001** | **0.0001** | | | | |
| | 1 Year | Z score | 14.22 | 16.16 | 15.51 | 12.29 | 12.24 | 12.18 | | | |
| | | p-value | **0** | **0** | **0** | **0** | **0** | **0** | | | |

| | | Control | | | | | Mechanical | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Before** | **1 Year** | **2 Years** | **8 Years (May)** | **8 years (Sept.)** | **Before** | **1 Year** | **2 Years** | **8 Years (May)** |
| 2 Years | Z score | 16.15 | 18.21 | 17.56 | 13.68 | 13.66 | 14.23 | 2.05 | | |
| | p-value | **0** | **0** | **0** | **0** | **0** | **0** | 0.03 | | |
| 4 Years (May) | Z score | 6.74 | 7.33 | 7.03 | 7.35 | 7.22 | 5.48 | -0.16 | -1.1 | |
| | p-value | **0** | **0** | **0** | **0** | **0** | **0** | 0.46 | 0.16 | |
| 4 years (Sept.) | Z score | 9.28 | 10.2 | 9.79 | 9.42 | 9.3 | 7.66 | -0.11 | -1.42 | 0.06 |
| | p-value | **0** | **0** | **0** | **0** | **0** | **0** | 0.47 | 0.1 | 0.47 |

# APPENDIX E

Appendix E: Dunn's table for before and after comparisons of native and non-native diversity.

Gold Bluffs Beach's Dunn's test after Kruskal Wallis between each treatments, manual, mechanical and control, for native species Shannon diversity index before removal (July 2012-January 2013), and 4 years after removal (September 2017)(bolded p-values are less than 0.05)

| | | Control Before | Control After | Manual Before | Manual After | Mechanical Before |
|---|---|---|---|---|---|---|
| Control After | Z test | -0.76537 | | | | |
| | p-value | 0.2562 | | | | |
| Manual Before | Z test | -3.92383 | -3.04006 | | | |
| | p-value | **0.0002** | **0.0025** | | | |
| Manual After | Z test | -4.2429 | -3.37222 | -0.45862 | | |
| | p-value | **0.0001** | **0.0009** | 0.3233 | | |
| Mechanical Before | Z test | -4.71226 | -3.82849 | -0.96562 | -0.48578 | |
| | p-value | **0.0000** | **0.0002** | 0.2279 | 0.336 | |
| Mechanical After | Z test | -1.80439 | -0.93371 | 2.506221 | 2.902415 | 3.450618 |
| | p-value | 0.0534 | 0.219 | **0.0102** | **0.0035** | **0.0008** |

. Gold Bluffs Beach's Dunn's test after Kruskal Wallis between each treatments, manual, mechanical and control, for non-native species Shannon diversity index before removal (July 2012-January 2013), and 4 years after removal (September 2017)(bolded p-values are less than 0.05).

| | | Control Before | Control After | Manual Before | Manual After | Mechanical Before |
|---|---|---|---|---|---|---|
| Control After | Z test | -0.715 | | | | |
| | p-value | 0.254 | | | | |
| Manual Before | Z test | -1.308 | -0.482 | | | |
| | p-value | 0.119 | 0.315 | | | |
| Manual After | Z test | 1.438 | 2.252 | 3.316 | | |
| | p-value | 0.103 | **0.0182** | **0.0010** | | |
| Mechanical Before | Z test | -4.687 | -3.860 | -4.138 | -7.362 | |
| | p-value | **0.00** | **0.0001** | **0.0001** | **0.00** | |
| Mechanical After | Z test | 2.404 | 3.218 | 4.490 | 1.149 | 8.536 |
| | p-value | **0.0135** | **0.0012** | **0.00** | 0.144 | **0.00** |

Little River's Dunn's test after Kruskal Wallis between each treatments, manual, mechanical and control, for non-native species Shannon diversity index before removal (2009), and 8 years after removal (September 2017)(Bolded p-values are less than 0.05).

| | | **Control Before** | **Control After** | **Mechanical Before** |
|---|---|---|---|---|
| **Control After** | Z test | 2.33 | | |
| | p-value | **0.0120** | | |
| **Mechanical Before** | Z test | -0.27 | -2.59 | |
| | p-value | 0.39 | **0.0072** | |
| **Mechanical After** | Z test | 5.24 | 2.65 | 5.54 |
| | p-value | **0.00** | **0.0080** | **0.00** |

# APPENDIX F

Appendix F: Gold Bluffs Beach Shannon diversity index before treatment and 4 years after treatment on native and non-native plant species.

| Treatment | Time<br>Plant type | Before<br>Mean | Before<br>Standard Deviation | Before<br>Dunn's Group | After<br>Mean | After<br>Standard Deviation | After<br>Dunn's Group |
|---|---|---|---|---|---|---|---|
| **Control** | Native | 0.021 | 0.117 | a | 0.053 | 0.184 | a |
| | Non-native | 0.071 | 0.205 | wx | 0.108 | 0.273 | w |
| **Manual** | Native | 0.185 | 0.356 | b | 0.195 | 0.360 | b |
| | Non-native | 0.154 | 0.377 | w | 0.032 | 0.154 | xy |
| **Mechanical** | Native | 0.246 | 0.446 | b | 0.091 | 0.242 | a |
| | Non-native | 0.258 | 0.413 | x | 0.030 | 0.050 | y |

# APPENDIX G

Appendix G: Little Rivers Shannon diversity index before treatment and 4 years after treatment on native and non-native plant species

| | | Before | | | After | | |
|---|---|---|---|---|---|---|---|
| **Treatment** | **Plant type** | **Mean** | **Standard Deviation** | **Dunn's Group** | **Mean** | **Standard Deviation** | **Dunn's Group** |
| **Control** | Native | 0.050 | 0.184 | x | 0.074 | 0.214 | x |
| | Non-native | 0.542 | 0.539 | a | 0.240 | 0.407 | b |
| **Mechanical** | Native | 0.049 | 0.200 | x | 0.010 | 0.078 | x |
| | Non-native | 0.576 | 0.602 | a | 0.034 | 0.148 | c |

# APPENDIX H

Appendix H: Tolowa Dunes Shannon diversity index 7 years after treatment on native and non-native plant species

| | | After | | |
|---|---|---|---|---|
| **Treatment** | **Plant type** | **Mean** | **Standard Deviation** | **Dunn's Group** |
| **Control** | Native | 0.4167913 | 0.466931 | a |
| | Non-native | 0.1037884 | 0.2525012 | x |
| **Manual** | Native | 0.7872416 | 0.4951898 | b |
| | Non-native | 0.09063261 | 0.2498491 | x |

# APPENDIX I

Appendix I: Gold Bluffs Beach mean *Ammophila arenaria* cover

| **Treatment** | **Time** | **Mean Cover Class** | **Standard Deviation** |
|---|---|---|---|
| **Control** | Before | 4.098039216 | 2.009073844 |
| **Control** | 1 Year Post-treatment | 4.405228758 | 1.961598128 |
| **Control** | 4 Years (May) Post-treatment | 2.064865 | 1.596909 |
| **Control** | 4 Years (September) Post-treatment | 2.294686 | 1.719427 |
| **Manual** | Before | 3.896551724 | 2.087409805 |
| **Manual** | 1 Year Post-treatment | 2.513888889 | 1.404219969 |
| **Manual** | 4 Years (May) Post-treatment | 1.355422 | 0.6325998 |
| **Manual** | 4 Years (September) Post-treatment | 1.232955 | 0.5315684 |
| **Mechanical** | Before | 5.154411765 | 1.703498259 |
| **Mechanical** | 1 Year Post-treatment | 1.132352941 | 0.361249345 |
| **Mechanical** | 4 Years (May) Post-treatment | 1.078788 | 0.2702275 |
| **Mechanical** | 4 Years (September) Post-treatment | 1.017143 | 0.1301761 |

# APPENDIX J

Appendix J: Little River mean *Ammophila arenaria* cover

| **Treatment** | **Time** | **Mean Cover Class** | **Standard Deviation** |
|---|---|---|---|
| **Control** | Before | 4.245 | 1.895505 |
| **Control** | 1 Year Post-treatment | 4.448 | 1.888269 |
| **Control** | 2 Years Post-treatment | 4.388 | 1.485356 |
| **Control** | 8 Years (May) Post-treatment | 4.9733 | 1.294201 |
| **Control** | 8 Years (September) Post-treatment | 4.7721 | 2.111928 |
| **Mechanical** | Before | 4.052 | 2.9 |
| **Mechanical** | 1 Year Post-treatment | 1.228 | 1.171968 |
| **Mechanical** | 2 Years Post-treatment | 0.788 | 1.15429 |
| **Mechanical** | 8 Years (May) Post-treatment | 1.2 | 0.406838102 |
| **Mechanical** | 8 Years (September) Post-treatment | 1.156 | 0.4070315 |

# APPENDIX K

Appendix K: Tolowa Dunes mean *Ammophila arenaria* cover

| Treatment | Time | Mean Cover Class | Standard Deviation |
|---|---|---|---|
| **Control** | 7 Years (May) Post-treatment | 3.744444444 | 2.5596748 |
| **Control** | 7 Years (September) Post-treatment | 4.111111 | 2.658226 |
| **Manual** | 7 Years (May) Post-treatment | 1.043956044 | 0.330389935 |
| **Manual** | 7 Years (September) Post-treatment | 1.022222 | 0.1482314 |